

High School Science Series

# Motion and Force

## Part 1 - Motion



an eklavya publication

Simple and Complex Motion

Types of Motion

What is Motion?

Recognising Motion

Quantifying Motion

# Motion and Force

## Part I - Motion

Acceleration in One-Dimensional Motion

Average and Instantaneous Speed

Speed

Predicting Motion

Uniform and Non-Uniform Motion



# Motion and Force

## Part 1 - Motion

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What kind of work or career do you want to take up?



I want to design a rocket which will go to the sun.

I want to drive racing cars.

I want to make artificial wings which can help us fly.

I want to make a cricket bat which will make hitting a sixer easy.



Dear children, I'm sure your friends will also like to do similar things in the future. But to do that, you all will have to choose appropriate courses of study and one thing which all of you will need to study is the science of motion and force!

## High School Science Series

For many years now, Eklavya and its Academic Resource Group have been deliberating upon high school science curricula. Science is currently taught in schools as general science till class X, and the prescribed textbooks focus on introducing students to a large variety of topics in a cursory manner. We therefore felt that there was a strong need to develop resource materials for teachers and students in line with the philosophy of the Hoshangabad Science Teaching Programme (a pioneering educational initiative that spanned three decades, in over a thousand schools of some districts of Madhya Pradesh). Members of Eklavya, science teachers, scientists, educationists and others interested in education, all put their heads together to develop a series of modules. These books are each the outcome of extensive collaborations—workshops, discussions, field trials and testing. They are designed to convey a broader understanding of some concepts and topics covered in school syllabi.

This module 'Motion' is the first of a two part series on motion and force. The result of several teacher training sessions and classroom trials conducted by Eklavya, it is meant as a resource material for teachers. Each section has pedagogical notes (text in grey background). They explain the rationale of the treatment used in developing that particular topic. At places, alternative approaches have been suggested. The main text develops the subject with the help of real life examples, hands-on activities and problems for students to think about and try solve. The activities are also a tool to introduce students to the various aspects of experiments and data analysis.

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# About the Module

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We live in a world that is constantly moving. Motion or movement of objects and people is something we come across every day. Understanding motion is a basic requirement for almost all branches of the natural sciences (including physics, chemistry and the life sciences) and engineering. Most properties of matter can be traced to the motion of the fundamental particles within it. The motions of electrons and other sub-atomic particles govern the physical and chemical properties of the elements. In biology, the movements of cells and sub-cellular units govern the interactions leading to metabolic processes. Even economics is the study of how money moves.

However, the question which confuses us sometimes is whether things are actually moving the way we perceive them or not. Think of watching trees from the window of a moving train. Are you moving forward, or are the trees moving backward? Similarly, we see the Sun move across the sky from east to west but current wisdom says that the Sun appears to move because of the Earth rotating from west to east on its axis. As these examples show, our intuitive ideas of motion based on visual observation do not always give the real picture. Then, how can we find out what is actually happening? Science looks for answers by using a combination of observations made under controlled conditions (experiments) and logical analysis. The understanding of any natural process can be used to make accurate predictions about it and to also develop new technology. For example, knowledge of the laws of motion and force allows for the times of eclipses to be predicted well in advance. The same knowledge has also led to the development of rockets which travel to the moon and back.

This module is an attempt to get you thinking about some of these issues. We will develop the basic concepts necessary to analyse motion and the effects of force on motion. The module is in two parts: the first part deals with describing motion (kinematics), and the second part deals with the relationship

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between force and motion (dynamics). Motion is relatively easier to grasp because it is a phenomenon we all can see. Also, the measurement of quantities like speed and acceleration can be demonstrated and understood more easily. Force is a more abstract concept and is experienced only by the effect it has on motion. Therefore, we start with motion—its definition, measurement and mathematical treatment. Further, to keep things simple we stick to linear motion. Once the basic concepts are understood, more complex motions (e.g. motion along a curve, oscillatory motion, rolling motion or a combination of several types of motion) can be analysed using these concepts or by building upon them.

We presume that anyone reading this module has a basic understanding of measurement and graphs. If that is not the case, we suggest that you first go through the two appendices on graphs and measurement, as well as the relevant chapters in the *Bal Vaigyanik* textbooks published by Eklavya.

The text of the module is interspersed with various examples and activities. They are designed to make the reader pause and think about what is being discussed. Detailed discussions of some topics, e.g. the scientific method, limitations and errors in any measurement, etc. have been moved to the appendices so that the main text reads smoothly.

The problems given at the end have been chosen to test whether the concepts discussed in the text have been properly understood. Therefore, do attempt them all to get the most out of this module.

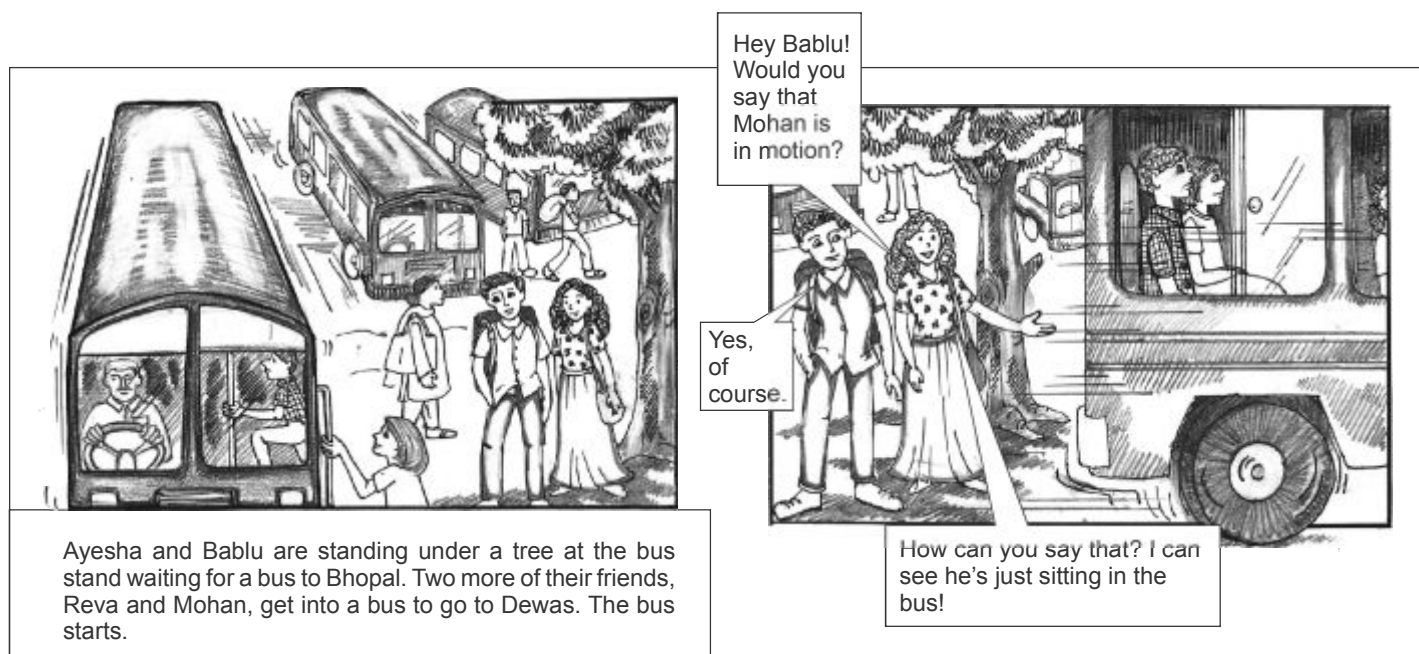
And lastly, but most importantly, this module is only a beginning. If it helps stimulate students (this includes all of us reading this module) to read more, learn more, question more and do more experiments, we would have achieved our aim.



# What is Motion ?

A good starting point is to find out what students already know. So you can start by putting questions like these to the class: “What is motion?” or “How can you know if something is in motion?” Most students would have studied something about motion by the 8th standard and will come up with some answers. However, their descriptions may not be complete. Any missing components can be brought out by discussing suitable examples.

For example, the children may feel that motion is a 'change in position' with 'time'. Though correct, this answer is not complete. What is missing is the explicit phrase that the change in position is with respect to a **point of reference**. To bring this out, you can use the conversation shown in the cartoon strip below. You can have four children enact it. A discussion should follow so that the children understand what the point of reference in any given motion is, and the role of the observer in understanding motion. You can use some more examples like the ones given next.



Yes but the bus is moving. Isn't it?



So what?

You never believe me. Ask Reva.

Reva, do you think Mohan is moving?



No, Mohan is not. He is just sitting in one place!

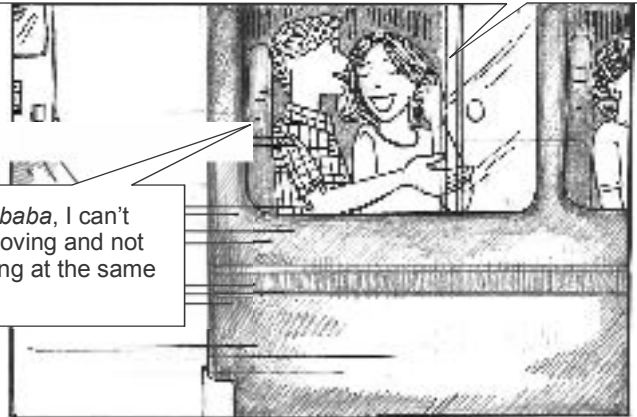


Ayesha tells this to Bablu. He snatches the phone from her and says irritably to Reva,

Can't you see that the bus has moved away from the tree and Mohan is in the bus? The bus is moving and Mohan's moving along with it.

But I am also in the bus! To me it does not look as if Mohan is moving. He isn't moving towards me or away from me.

Arre baba, I can't be moving and not moving at the same time!



What do you think is happening? How do we decide whether something is moving or not?

**Example 1.** Observe the moon on a windy night with a fair bit of cloud cover in the sky. As a cloud passes in front of the moon you sometimes think it is the moon which is moving behind the cloud. What would you think if you were to observe a tree at the same time? (Fig. 1)



Fig.1 'Hide-and-seek' with the clouds

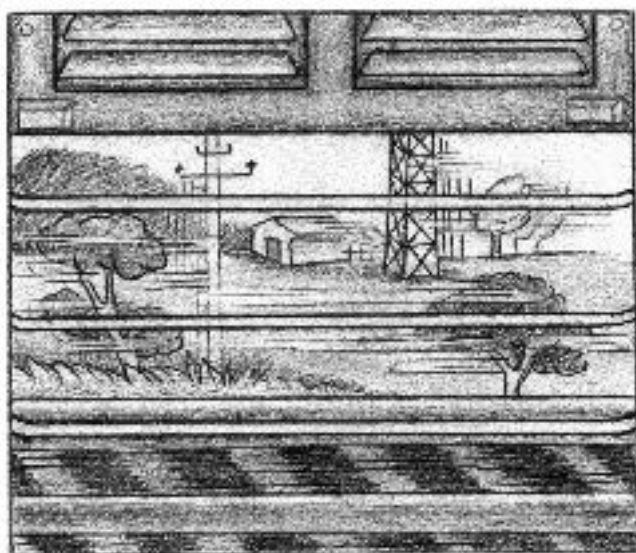


Fig. 2 Scenery flashing past a moving train

**Example 2.** This is the classic example of watching the scenery from the window of a moving train. When the train is passing through open countryside, we feel that the bushes or lampposts near the train are moving in the opposite direction, but the trees further away seem to be moving in the direction of the train. We do know that both the lampposts and the trees are fixed to the ground; so, why this illusion? (Fig. 2)

**The motion of an object is its relative movement with respect to a point of reference as measured by an observer.** The point of reference may be the person making the observation or some other point or object visible to the observer. For example, when trying to catch a ball thrown at us, we judge the movement of the ball by its position with respect to ourselves. When writing, we judge the position of the pen with respect to a line on the page or the page edge. Imagine writing something while sitting in a moving train. We, along with the paper we are writing on, are moving with the train. But we write (if the train is moving smoothly) as though we are sitting on a chair in a classroom. The common feature in both the examples is that the point of reference is assumed to be stationary and the movement is observed with respect to it. Thus, we don't bother whether our seat is moving or not. As long as we hold the paper fixed with respect to ourselves, we can write.

What happens when we try to play 'catch' in a moving train?

# What is P.T. Usha Doing?

Look at the photograph of the famous athlete P. T. Usha in Fig. 3. What do you see in it?

Did you answer “P. T. Usha is running on the beach”? The photograph only shows that she has one foot on the ground and the other off it. You can lift one foot off the ground even while standing still. Try now!

From a still photograph we cannot be certain whether she is running (moving) or standing still. For that we need to observe her at different points in time.

Similarly, in the case of the Sun, Moon or a constellation, they look still when we look at them. But if we observe them after half an hour, or sometimes after a few hours, only then can we see that they have moved.

We often use statements like, “I am walking now” or “You are driving very fast now”. It is difficult to understand that when we say ‘now’, we are actually talking about a small interval of time during which our positions have changed. This will be clearer later when instantaneous and average speeds are discussed.



Fig. 3 P.T. Usha on a beach

P. T. Usha, also nicknamed the Payyoli Express, came from a small village in Kerala and is one of the most successful women athletes in recent times. Between 1983-89, Usha garnered 13 golds at the Asian Track and Field meets. In the 1984 Los Angeles Olympics, Usha became the first Indian woman (and the fifth Indian) to reach the finals of an Olympic event by winning her 400 m hurdles semi-finals. In the finals, she lost the bronze by 1/100th of a second. Usha has won 101 international medals, so far. Her six medals, including five golds, at the 6th Asian Track and Field Championship at Jakarta in 1985 is a record for a single athlete in a single international meet.

Time and motion are irretrievably connected to each other. We need to know time to deduce motion, and motion to measure time. All clocks depend on some motion which is considered the standard. In a sand-clock, all the sand flows down a hole in a fixed period of time, in a sundial the shadow moves from one marked position to another every minute or hour, in a modern day watch a crystal vibrates with a fixed frequency, and in an atomic clock it is the fixed time of the electron orbiting in an atom that makes it possible for us to measure time.

Studies have shown that many misconceptions regarding motion arise from the fact that the passage of time is not given the same importance as the change in position. This is possibly because we see the moving object changing its position and the pictures of the object in different positions are stored in our mind. However, time is not sensed directly, and many times we are not even aware of the passage of time.

Discuss whether the following statements can be correct:

- a. I walked for an hour yesterday.
- b. I am always running.
- c. You are standing still.
- d. Mohan is standing still and waving his hand.

Some of these statements have been deliberately chosen to be ambiguous. Discussing these or similar statements in detail will reinforce the concepts of time and the points of reference for the students.

## Types of Motion

Ask everyone in the class to remain in their places, to look around and identify objects that are moving. The replies could list: the teacher walking in the classroom, a ceiling fan running in the room, leaves fluttering on trees outside, birds flying in the sky, people walking in the corridor outside, ants or flies in the room, etc. Some may also come up with: the heads of other people looking around, blinking eyes, moving fingers, etc.

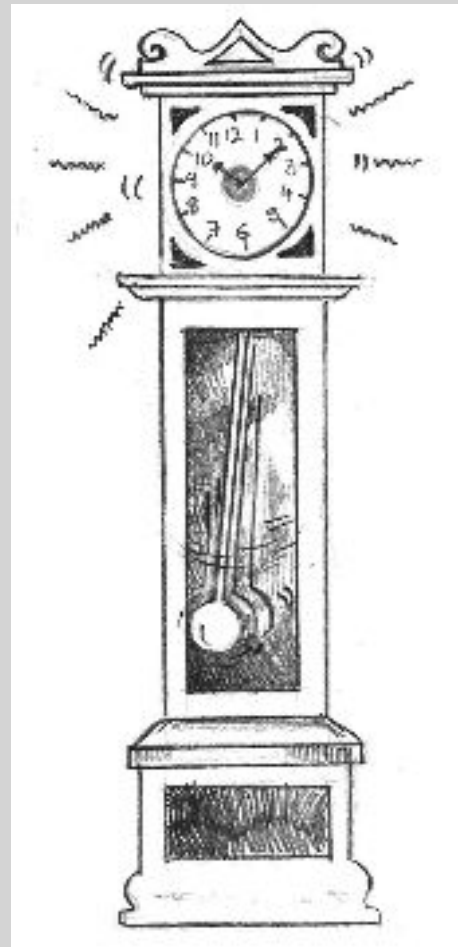
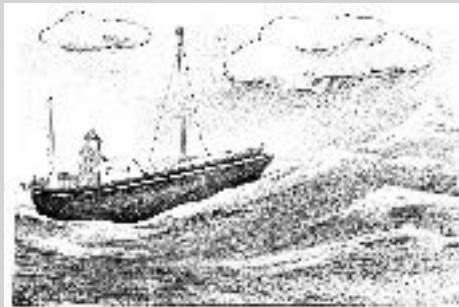
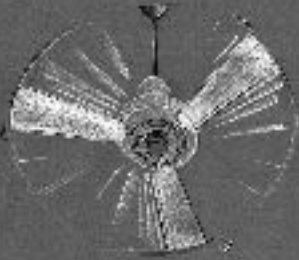
How many different kinds of motions can you think of? We use different words like walking, running, jumping, waving, vibrating, shaking, rotating, falling, etc. to describe different kinds of motions.

Depending on the path that a moving object takes, the motion can be called:

- a. Linear—moving in a straight line, like a person walking on a straight path, free fall.
- b. Curvilinear—moving ahead but changing direction, like a snake.
- c. Circular—moving in a circle, like a fan.
- d. Periodic—coming back to the same position after a fixed time interval, like a pendulum.

Make a table of the different types of motions you can see. Into which of the above four categories do they fall?

## Various Motions from Everyday Life





# Complex Motion

**Example 3.** While playing with a top as a child, you may have noticed that it rotates around its axis (the pin) while moving around on the floor (Fig. 4).

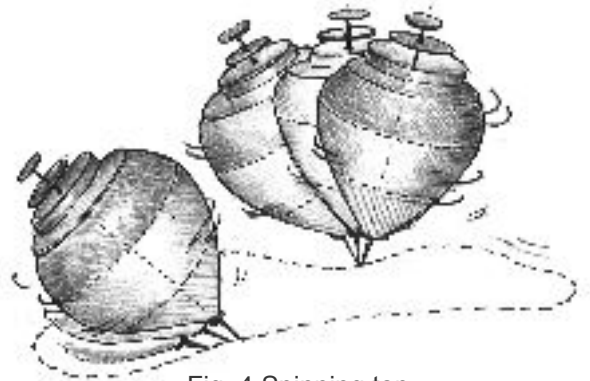


Fig. 4 Spinning top

**Example 4.** In the case of a moving bus, tyres rotate about their axles and move forward, too. The steering wheel rotates about a different axis while moving ahead with the bus (Fig. 5).

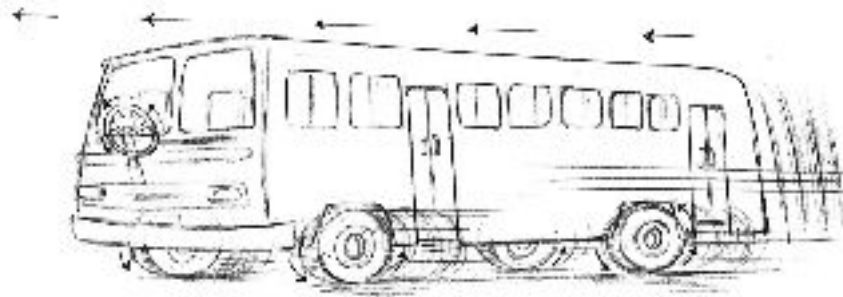


Fig. 5 Motions of different parts of a moving bus

**Example 5.** Similarly, the forward motion of a cycle is also a combination of different motions of its various parts. Look at the photograph of a boy cycling down the road. The boy and the cycle together are moving in a certain direction, while the boy's feet and the cycle's pedals are moving in a circle. The wheels of the cycle are, simultaneously, revolving around their respective axes as well as moving ahead (Fig.6).

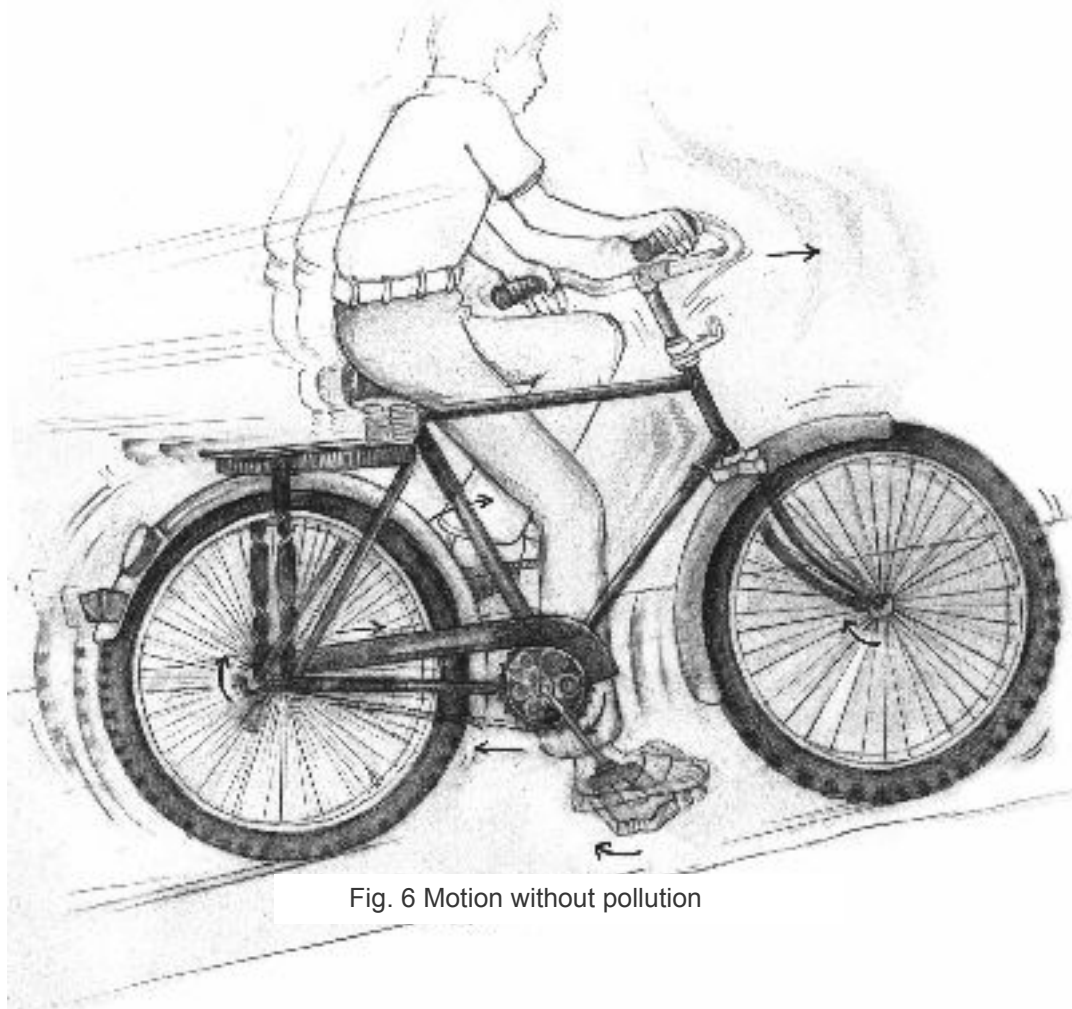


Fig. 6 Motion without pollution

Look around you at moving things and see how many of the motions are complex (a combination of more than one type of motion). Try to identify the different motions that combine to make up an observed complex motion.

For now, we will restrict our discussion to motion in a straight line. We will see that the quantitative description of this linear motion is relatively simple. Therefore, it is easier to understand the basic concepts involved in this kind of motion without getting lost in any numerical complexity. Complex motions can be understood by breaking them into simpler parts, analysing each part independently and then summing them all up again. This is one of the ways in which we learn. When learning to sew, we start with the running stitch, and then go on to hemming and the back stitch. Or, in language, when faced with a complicated text full of new words and terms we refer to a dictionary, which (often) uses simpler words to explain the meaning of a word we find difficult to understand. We will be following this approach to understand motion. We will begin with the simplest scenario, and by trying to understand it we will build a theory of motion. This theory will then be expanded to cover more complicated motions. Working this way, we will move towards a better understanding of real-life motions.

Most real life motions are complex, that is, a combination of more than one type of motion. A ball rolling on the floor will have forward linear motion and simultaneously be rotating around its axis. One approach for studying a complex phenomenon is to break it into simple components, formulate a theory to explain the simple components and then add up the components to get a theory to explain the complex phenomenon. This is called the reductionist approach in science (see box).

## The Reductionist Approach

This is a basic approach used in science to explain any phenomenon. As you have seen in the examples discussed in the text, most of the motions that we observe around us are complex processes, whether it is a child riding past on a cycle or a moving railway engine. In order to understand this complexity, a common method used is to try and figure out what factors affect the observed processes. The next step is to study the effect of each of the factors. In order to do this, we vary the factors one by one. That is, in one experiment, we first change one factor while keeping all the others constant as far as possible. In another experiment, we vary the next factor, and so on, till we have studied how the change in each factor independently affects a process. Then, the results of these experiments are put together to try and explain the complex process.

Here, we are making a huge assumption—that the whole phenomenon is merely the sum of its parts, of the factors that influence it. This means that we are assuming that when all the factors that influence a phenomenon interact with each other, we get only the observed phenomenon. This is called ‘the reductionist approach’, since we reduce the problem into its components, analyse the components and try to arrive at an explanation. Is the assumption we make in the reductionist approach valid? All our successes in understanding various physical and chemical processes have come from applying this approach.



# Quantifying Motion

To recapitulate, the motion of an object is its **change in position** with **time**. This change of position is measured with respect to a **point of reference** by an **observer**. To quantify motion, we need to measure the change in position with respect to a point of reference as well as the elapsed time. However, very often, we don't explicitly specify the point of reference but assume that the measurements are taken with respect to a convenient point of reference.

The point of reference and the observer, together make the **frame of reference**.

Let us first look at the change in position of an object in motion. This can be found out by measuring the distance covered by a moving object.

What instruments can you use to measure distances?

**Example 6.** Take two identical, long objects like two dusters or two pencils. You will also need a ruler to measure distance. Keep the two pencils side by side on a table and mark their positions with a piece of chalk. Move the second pencil some distance ahead, keeping it aligned with the first pencil (Fig. 7). Mark the position of the second pencil. Now, measure by how much distance the second pencil has been moved. Ask your friends to do the same exercise. Did you all get the same result? If not, why not?

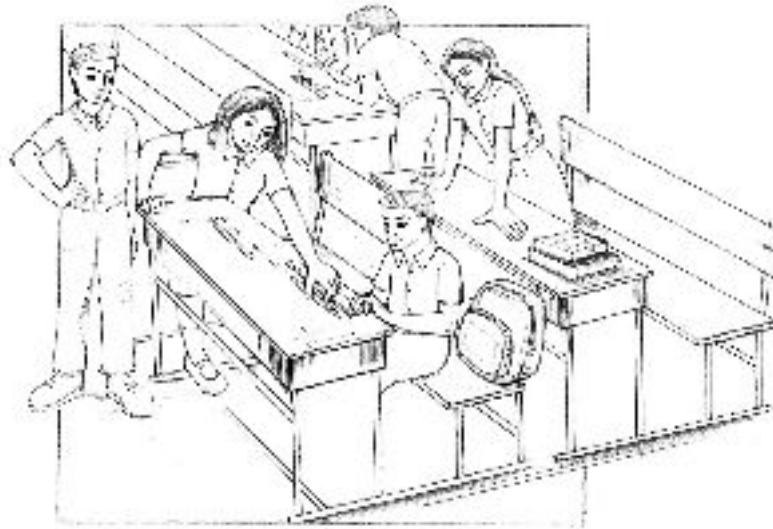


Fig. 7 How far did the pencil move?

**Example 7.** I have a small ball with a face on it (Fig 8). I roll the ball on the floor from one corner of the room to the other. If the room size is 10'x10',

- What is the net distance moved by the ball?
- Is the net distance moved by one of the eyes the same as the distance moved by the ball?

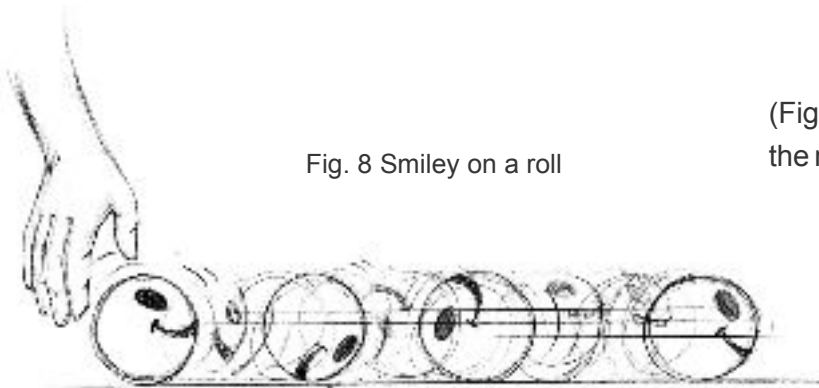


Fig. 8 Smiley on a roll

These questions can lead to a discussion on the following points. The answer to (a) will depend on which corners are chosen—adjacent or diagonal. Also, each point on the ball makes a compound motion, as it is rotating around the centre of the ball which itself is moving in one particular direction on the floor. Generally, we call the motion of the centre of the ball the 'motion of the ball'. In looking at the forward linear motion, the rotation of the ball around its axis is ignored. We also ignore the inaccuracies in distance measurement arising from the finite size of the ball. A discussion can be held on the conditions under which these assumptions are valid.

**Example 8.** In the picture below, the bus has moved from right to left (Fig. 9). Can any of the marked distances be taken as the distance covered by the bus between the two positions? If yes, which one would you choose and why? If no, then what is the appropriate distance?

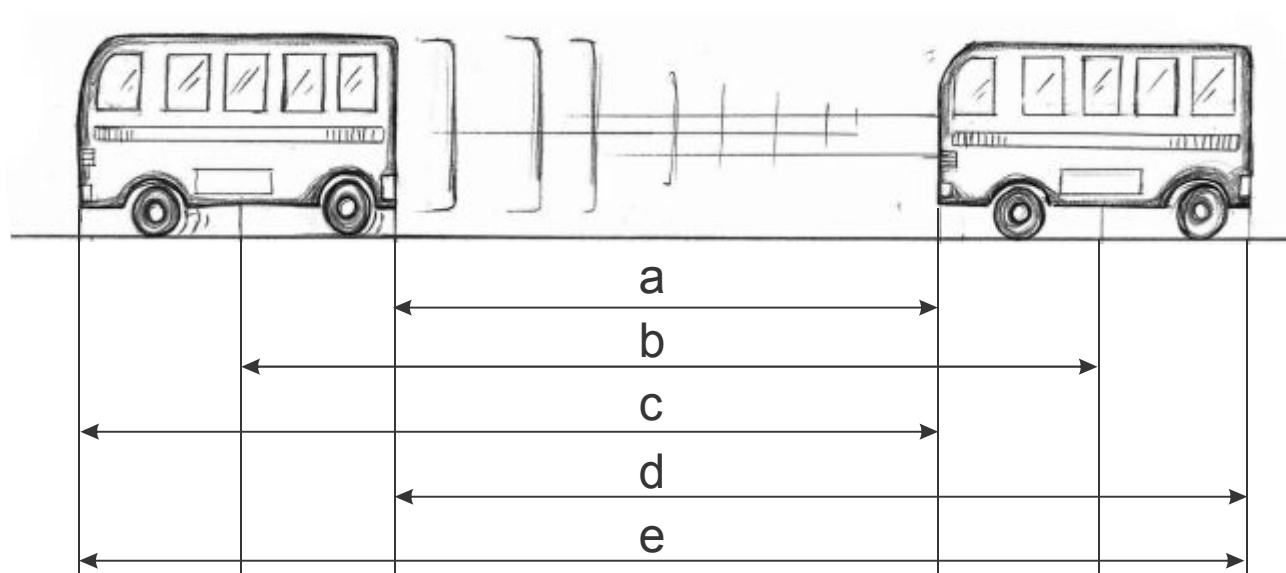


Fig. 9 Front end / back end—which points to measure between?

In measuring the distance covered by a moving object, there are two issues to consider. First, real objects have a finite size and second, different parts of the moving objects can execute different motions. The examples given here are meant to illustrate these two points. The second point can be illustrated best by the example of a bicycle or a bus, both of which are familiar to students. Here, we have discussed the bus, the cycle can be given as a problem to the students. What are the assumptions underlying this estimation of the change in the position of the bus? We selected one point on the bus, measured its change in position and assumed that the whole bus has moved by that much distance ignoring the movements of things like the wheels and the people sitting inside. We also assumed that the shape and size of the bus remains the same at both positions. In effect, we assumed the bus to be a single rigid body. This kind of idealisation is used many times in science so that universal principles underlying observed phenomena can be deduced without getting lost in complicated calculations.

Let us now look at time measurement. That is, we want to measure how much time elapses during a certain motion. How would you measure the time taken to go home from school? Can you use the same method to measure the time taken to throw a ball from one end of a room to the other? Try it.

In some of the activities described later in this module, we suggest the use of a stopwatch (Fig. 10). Good stopwatches, which show up to a 100th of a second will be very useful for your experiments. The figure shows such a stopwatch available in Indore markets. Generally, easily available, commercial digital stopwatches are multi-functional. So, you might need to change the mode of the one you buy to the 'timer' setting. You may refer to its manual to learn how to switch between the different modes, and to learn how to start, stop and reset the stopwatch. The other option is to use the 'stopwatch' function in your mobile phone.



Fig. 10 A typical electronic timer/ stopwatch

## All Together

Ask the students to start their stopwatches when you clap/whistle and to stop them with the sound of your second clap/whistle. To start with, keep a sufficient gap between two consecutive claps/whistles. As the students get more and more familiar with the functions of the stopwatch keys, reduce the time between the two claps/whistles. It is necessary that they learn to use the stopwatch as accurately as possible to achieve good experimental results in the activities suggested later in the module.

## Click-Click, Quick-Quick

Another interesting activity to help familiarise students with stopwatches is one in which they are asked to check their reaction times. To do this, students are asked to start and stop their stopwatches as fast as they can. The recorded time interval is the smallest that each one can measure. Repeat this activity 20-25 times. The arithmetic mean of all the readings taken by a student will give the 'average reaction time' of that person. In a classroom experiment, the data can be considered to be reliable if the number of readings taken is much larger than the average reaction time (at least 3 to 5 times). You can verify this in the 'All Together' activity. Try to find the shortest time between two claps/whistles that can be measured accurately.

# Speed

Now that we have learnt something about measuring distance and time, let us see if we can go further and measure motion. One of the first things we notice about a moving object is how fast it moves. Fastness or slowness is decided by speed. For example, you are getting late for school. One neighbour offers to drop you on his bicycle. Another neighbour offers to take you on his motorbike. Which one would you choose if you want to get to school quickly, and why?

Students at the high school level (13-15 years) already have some concept of speed in the context of fastness or slowness of motion. Hence, examples similar to the one above can be used to start a discussion on the quantitative measurement of speed.

A motorbike can go at a higher speed than a bicycle, and you can reach your school faster on your neighbour's motorbike. However, speed is not a quantity that can be directly measured. It is calculated by dividing the distance covered by a moving object, by the time taken to do so, or

$$\text{Average Speed} = \frac{\text{Total distance moved}}{\text{The time taken to cover this distance}}$$

Notice, that we have qualified speed by adding 'average' to it. This distinction will be discussed in detail a little later. First, let us have some fun measuring speed.

The activities on the following pages are designed to break the monotony of the classroom and to get the students moving. They can be done by rolling a ball, moving a chalk or stone by hand, or by observing the ants moving on the floor—by observing anything that moves in a straight line and slowly enough so that the time taken for the activity can be measured using a stopwatch. Students can also be asked to make similar measurements at home and discuss the results in class. If a stopwatch is not available, time can alternatively be measured by the seconds hand of a clock or watch, or the clock in a mobile phone. A ruler or measuring tape will do for measuring distance. Students should be encouraged to discuss the problems they face in making distance or time measurements for something moving very fast, the errors in measuring the distances moved by different objects, measuring distance or time for objects that do not move in a straight line, etc.

## The Racing Ants

We have all seen ants scurrying around. Can their motion be described as straight-line motion? Observe their motion and try to measure their speeds. Did you face any problem in determining their speeds? The following activity may help.

Collect some ants (Fig. 12), preferably of different varieties (make sure they do not bite you). Tie a coarse thread between two points such that the thread is stretched taut in the air at some height above the ground. One person with a stopwatch acts as a timekeeper. Place the ants, one at a time, on one end of the thread and note the time an ant takes to move along the thread, as well as the distance it covers (Fig. 13). For this, you can make a mark on the thread where you place the ant and start the stopwatch. Make another mark on the other end of the thread, and stop the stopwatch when the ant reaches this mark. Note the time each ant has taken to cover the distance between the two marks. Then, you can measure the length of the thread between the two marks. The ants may drop down from the thread midway! Can keeping some sugar at some distance help them stay on the thread? Try it and prepare a table of your observations. You can use Table 1 given below as a guide.



Fig. 12 Searching for ants

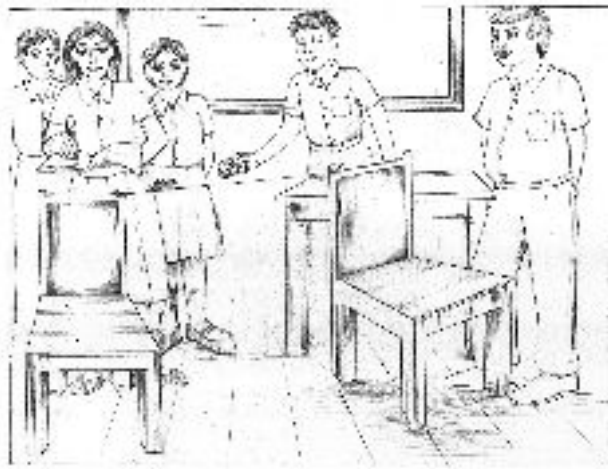


Fig. 13 Ants on a tight rope

Table 1

| S. No. | Name      | Distance | Time taken | Average Speed |
|--------|-----------|----------|------------|---------------|
| 1      | Black ant | 10 cm    | 2 s        | 5 cm/s        |
| 2      | Red ant   | 16 cm    | 4 s        | 4 cm/s        |
| 3      |           |          |            |               |

Which ant was the fastest? (After the experiment, do return the ants to where you took them from). Do you think there was some possibility of error in the measurements? Discuss how you can reduce such errors.

## Block Walk

The following example is designed to ease the students into visualising imaginary motion. It clarifies the relation and difference between speed and position. Students often get confused between them.

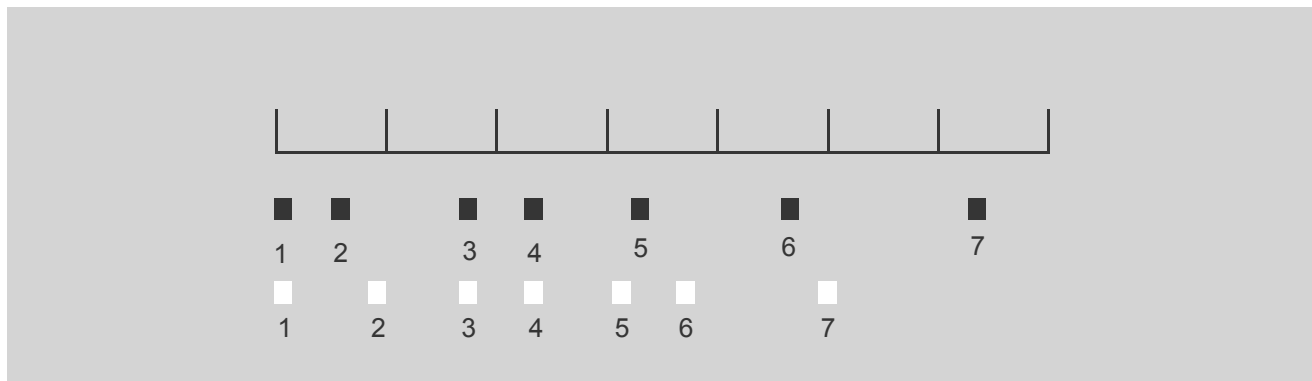


Fig. 14 The positions at each second of two blocks moving in parallel for 7 s. The lines above the blocks mark the distance moved by the blocks.

Two blocks, one white and the other black in colour, are being moved in straight lines parallel to each other. Their positions after every second are shown by the numbered squares in Fig. 14. The numbers show the time in seconds. The blocks are moving from left to right.

1. Which block has a higher average speed?
2. At what time were the two blocks at the same position?
3. When did the blocks have the same speed?
  - a. Between 2 s and 3 s
  - b. Between 3 s and 4 s
  - c. Between 5 s and 6 s
  - d. Never
4. When does the black block first overtake the white block?
  - a. Between 1 s and 2 s
  - b. Between 2 s and 3 s
  - c. Between 3 s and 4 s
5. When does the white block first overtake the black block?

# Units of Speed

This is a good place to explore the concept of units in some detail by taking speed as an example. The questions we aim to answer here are, (a) why are different units required in different situations, and (b) how to convert values from one unit to another.

In training sessions, we observed something curious. Many students, and even some teachers have a deep conviction that the only possible units of speed are m/s and km/h. Also, they found that conversion between the units of speed (which is a ratio of two quantities—distance and time) is slightly more complicated than that of, say, weight (e.g. converting between kg and g).

A vegetable seller weighs the vegetables in units like 250 g, 1 kg etc., but the trucks carrying vegetables coming into the *mandi* are weighed in tons. Just like there are different units for weight, there can be several units of speed. Some common examples are km/h (used for measuring vehicle speeds) and m/s (used in laboratory measurements). However, other combinations are also possible, like miles/h, inch/s etc., as long as a unit of distance is divided by a unit of time to get the unit of speed.

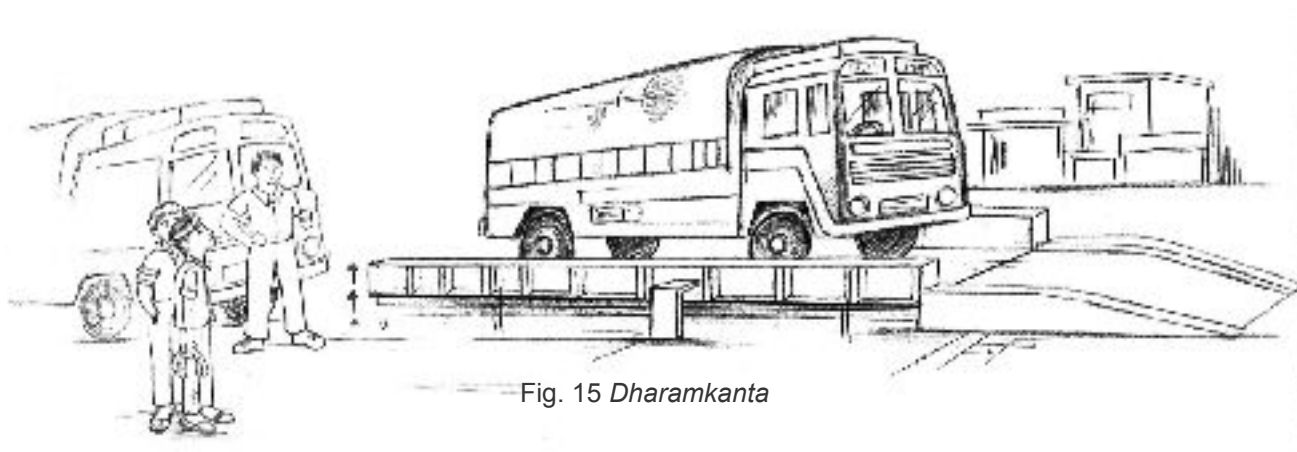


Fig. 15 *Dharamkanta*



Fig. 16 *Sabji mandi*

In the earlier activity on racing ants, can you use some other units for speed? (Hint: Measure distance in inches instead of cm).

### Conversion between units

The average speed of a bus is 36 km/h. How much would it be in cm/s?

We know  $1 \text{ km} = 1000 \text{ m} = 1000 \times 100 \text{ cm} = 1,00,000 \text{ cm}$

And  $1 \text{ h} = 60 \text{ min} = 60 \times 60 \text{ s} = 3600 \text{ s}$

So  $1 \text{ km/h} = 100,000 \div 3600 \text{ cm/s}$

Therefore  $36 \text{ km/h} = 36 \times 100,000 \div 3600 \text{ cm/s} = 1000 \text{ cm/s}$

Does this tell you why different units are required in different situations?

What units you would use for the speed of

a. A tortoise

b. A jet plane

One bus travels 4 km in 6 minutes. Another bus travels 3 miles in 10 minutes. Which one was faster? (1 mile = 1.6 km, approximately).

The famous Pakistani fast bowler, Shoaib Akhtar (also known as the 'Rawalpindi Express') was trying to set a bowling speed record of 100 miles/h. However, the stadium speedometer measured the speed in km/h. In one over, the values recorded were 158.3 km/h, 155 km/h, 142 km/h, 157.3 km/h, 148 km/h and 159.2 km/h. Do you think he reached his target in this over? Find out the record for the fastest bowling in international cricket.

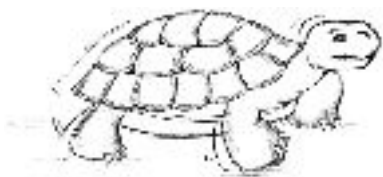
**Example 9.** You can practice some more conversions between units by doing the following exercise:

Table 2

| S.No. | Convert | to   | Using                                                              |
|-------|---------|------|--------------------------------------------------------------------|
| 1     | cm/s    | m/s  | $1 \text{ m} = 100 \text{ cm}$                                     |
| 2     | inch/s  | cm/s | $1 \text{ inch} = 2.54 \text{ cm}$                                 |
| 3     | km/h    | m/s  | $1 \text{ km} = 1000 \text{ m}$ and $1 \text{ h} = 3600 \text{ s}$ |



## Typical Speeds



tortoise: 0.1 m/s

person walking: 1.4 m/s



falling raindrop: 9-10 m/s



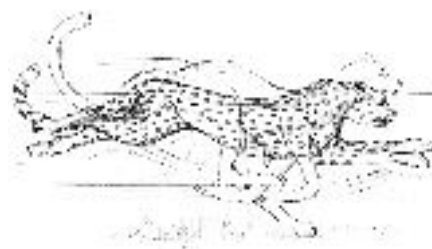
cat running: 14 m/s



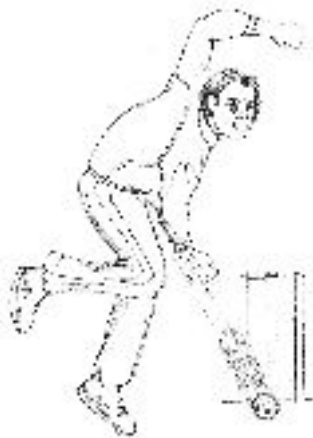
cycling: 20-25 km/h



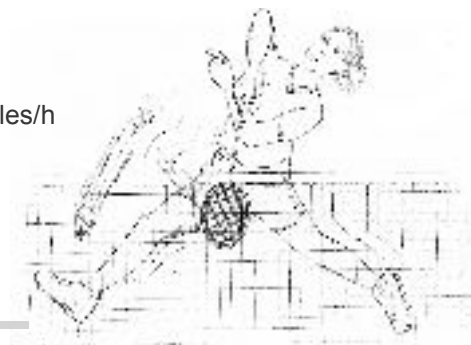
cheetah running: 31 m/s



bowling speed of fast bowlers: 90-100 miles/h



badminton smash: 80-90 m/s



passenger jet: 180 m/s



space craft: 5200 m/s



At this point it is worth getting a feel of the speeds we encounter in our world. The table on the left gives the typical speeds of some motions. Ask the students to add more items to the list and to guess their speeds. To get a feel of the magnitude of speed, take the walking speed as a reference and then compare how much faster or slower the other motions are. For example, a domestic cat can run at ten times a human being's normal walking speed, while a cheetah can run twenty times faster. Ask the students to find out how fast people can run to see if we can outrun a cat or a cheetah chasing us!

 Which is faster—the bowling speed of a fast bowler or a badminton smash?

### Projects

1. Choose a motion for speed measurements. It could be your baby brother's crawling speed, the running speed of your pet dog, the speed at which your friend cycles, the speed of water flowing in a canal, the speed at which a leaf falls from a tree etc. Make several measurements of the speed of the motion you have chosen, noting down the conditions under which you make the measurements. Now analyse (with some help from your teacher) the measurements to see if you can arrive at a figure for the typical speed of the motion under study.
2. Try to find the typical speeds of more animals. Make a chart listing animals (including humans) in the increasing order of their speeds. If you are good at drawing you can draw their pictures along the list. Now see if the predators are always faster than their prey!

# How Does a Leaf Fall?

Have you watched a dry leaf falling from a tree? Unless there is a strong breeze, the leaf tacks from side to side as it comes down. See the paths shown in the Figs. 17 and 18. Do you think it is as easy to measure the length of this path as that of a falling stone? Obviously not. So, how can we know the distance for the estimation of the leaf's speed? Well, if we are mainly interested in the downward motion of the leaf, we ignore the side-to-side swaying. The distance straight down divided by the time taken for the leaf to fall is taken as the average speed of the falling leaf. If you make this assumption and if the swaying motion is very small compared to the downward distance it travels, you will get a value close to the actual speed of the leaf. Can you think of an experiment to verify this assumption?



Fig. 17 No wind



Fig. 18 Windy day

Similarly, when analysing any real motion we often make the assumption that it is moving in a straight line and ignore small movements in other directions. The examples discussed further on make this assumption. While taking measurements in the activities, you can discuss the amounts of error caused by this assumption.

# Uniform and Non-Uniform Motion

It is possible that while doing all the speed measurement activities at least a few of the students would have noticed that the speed does not remain the same from the beginning to the end of the activity. If no one has made such an observation, start a discussion about it with the following example.

Imagine, that we are tracking a school bus from the bus stop near your home to your school. The bus arrives at the stop and you climb in. Then, the driver puts it in gear and the bus starts moving. The bus reaches the school after some time where it stops so you can get down. If we go by the definition given earlier, we measure the distance from your home to school, and divide this distance by the time taken to reach your school to find out the average speed of the bus. But, you might have also observed that when the bus started, it moved at a slower speed, and it picked up speed only after some time. The reverse happens before the bus comes to a stop. Does this mean that during the motion from one bus stop to another, the bus has moved at different speeds at different times? In that case, what do we mean by the speed of the bus and how do we measure it?

# Average and Instantaneous Speed

Suppose a bus moves straight from point A to point B in 30 seconds (Fig. 19). The distance from A to B is 300 meters. Then the average speed would be  $= 300 \text{ m} \div 30 \text{ s} = 300 \div 30 \text{ m/s} = 10 \text{ m/s}$ .

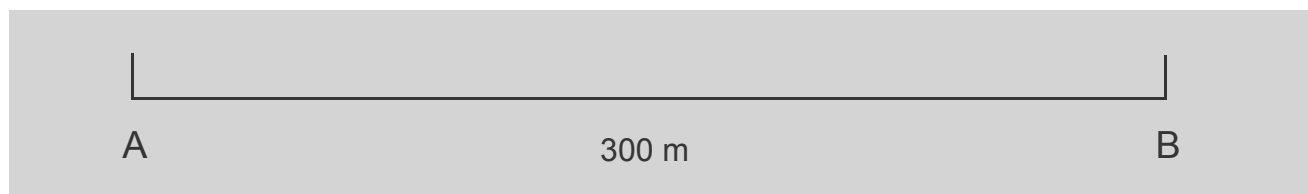


Fig. 19

Suppose we also make measurements at points between A and B (Fig. 20). We make the measurement from A to C, then C to D and so on. We then calculate the speed for each segment.



Fig. 20

We get the following values:

Table 3

| Points | Distance | Time taken | Segment speed |
|--------|----------|------------|---------------|
| A-C    | 20 m     | 2 s        | 10 m/s        |
| C-D    | 60 m     | 6 s        | 10 m/s        |
| D-E    | 120 m    | 12 s       | 10 m/s        |
| E-B    | 100 m    | 10 s       | 10 m/s        |

We find that the average speed within each segment is the same as the average speed between A and B, which is 10 m/s. This is therefore an example of **Uniform Motion**. That is, the speed remains constant throughout the motion.

Alternatively, let us suppose that the following values are obtained for measurements between the same sets of points:

Table 4

| Points | Distance | Time taken | Segment speed |
|--------|----------|------------|---------------|
| A-C    | 20 m     | 2 s        | 10 m/s        |
| C-D    | 60 m     | 10 s       | 6 m/s         |
| D-E    | 120 m    | 8 s        | 15 m/s        |
| E-B    | 100 m    | 10 s       | 10 m/s        |

The last column in this table too shows the average speed for each segment. But here, the distance of 60 m between the points C and D has been covered in 10 seconds (as compared to 6 s as given in Table 3). Therefore, the average speed between C and D here is  $60 \div 10 \text{ m/s} = 6 \text{ m/s}$ . The total time taken to cover the entire 300 m between the points A and B is still 30 s (add the values in the third column of Table 4). In the very beginning, we had calculated the average speed over the entire distance between A and B (which includes the segment CD) to be 10 m/s. How can we then explain the two different speeds for this segment?

This problem arises because we had initially considered only the total time taken to cover the total distance in calculating the average speed. It only means that if the object had moved at a constant speed of 10 m/s from A to B, it would have covered the distance in 30 s. It does not tell us anything about the time taken to cover the different parts of the total distance. As we can see above, it might be that the speed was less than the average value in some parts and more than the average value in some other parts. This kind of motion where the speed keeps changing is called **Non-Uniform Motion**.

You may well ask how we can know whether the speed of a moving object will remain uniform if we further divide the segments into even smaller parts. The answer is that, of course, we cannot, unless we actually make the measurements for the smaller segments. So, the only way we can know whether a motion is uniform, is by measuring the speed of the object in motion in smaller segments along its path of motion.

What is the smallest segment that can be measured? Think of the instruments you can use to measure distance and time (rulers, measuring tapes, watches, clocks, mobile phones) and the smallest values you can read on each instrument (this is also called the 'least count' of the instrument). This is how small a segment can be. For example, if you are using a watch with a seconds hand you can measure the distances traveled every second (the least count of your watch). You can then calculate the speed during each second and use these measurements to see if motion is uniform over a longer period of time (say 15 minutes). In such a case, we call the speed measured over each second the **Instantaneous Speed**.

If we had a way of measuring a smaller time interval, say, one tenth of a second, then we would call the speed obtained by the measurement over a tenth of a second as the instantaneous speed. Later on in the module, we will discuss how to depict motion using graphs. Then we will see how distance-time graphs can be used to work out the instantaneous speed. Whichever method we use, the term 'instantaneous speed' denotes '*the average speed over the least count of the time-measurement device*'.

## Calculating Averages

Children (and not only children), often make mistakes in calculating the average speed of non-uniform motion when speeds for all the segments of an entire path of motion are given. During teacher training sessions we realised that the difference between calculating the average of rates and calculating the average of simple numbers (that are not rates) is not clearly understood by many. The discussion in this section addresses this issue. One example is about exam marks and percentage marks (percentage is a rate, the amount of something per hundred) which is familiar to all students. The other example is about a purchase in a vegetable market. You can substitute this example with a different one more suited to the students' social environment, if required.

Calculate the average of the following seven numbers:

67, 55, 87, 64, 73, 42, 38.

To do this, you have to add them all and divide the sum by seven, thus getting 60.9.

But, suppose these numbers are actually Nida's marks in various subjects and her report card is as follows (Table 5):



Table 5

Fig. 21 *Dadima*, see my report card!

| Subject        | Maximum marks | Marks obtained | Percentage |
|----------------|---------------|----------------|------------|
| Hindi          | 100           | 67             | 67         |
| English        | 100           | 55             | 55         |
| Mathematics    | 100           | 87             | 87         |
| Social science | 100           | 64             | 64         |
| Science        | 100           | 73             | 73         |
| Craft          | 50            | 42             | 84         |
| Music          | 50            | 38             | 76         |

The percentage is the number of marks which would have been obtained had the maximum marks been 100. So, it is the ratio of marks given to the student, to hundred marks (the rate of marks per hundred). The percentage is calculated by dividing the marks obtained by the maximum marks and then multiplying the ratio by 100.

Now, if we have to find the average percentage (or what is sometimes wrongly called the 'total percentage'), what do we do? Do we take an arithmetic mean of all subject percentages? If we do that for the above table we get 72.29. You should check all these calculations yourself. If this is correct, then multiplying this number by the maximum marks and dividing by 100, should give us the total marks obtained. Let us see if that happens. The total of maximum marks is 600 so if the average percentage is 72.29, then the total number of marks obtained should be  $72.29 \times 600 \div 100 = 433.74$ . But if we add up the total marks obtained then we get only 426. Where have we gone wrong? If you go over the calculations, you will see that we treated ratios or rates as simple numbers. For any set of ratios, the averaging has to be done by adding all the numerators and denominators separately, and then taking the ratio of the two sums. You can try this with different sets of numbers.

Your father went to the *sabzi mandi* to buy potatoes. At one place he bought 6 kg of potatoes at ₹ 6 / kg, at another he saw a different variety of potatoes and bought 2 kg at ₹ 10/kg. What was the average price he paid for the potatoes?

If the students cannot do the above problem, solve it for them.



Fig. 22 Buying potatoes in the bazaar



Your father bought 6 kg of potatoes at ₹ 6/kg and 2 kg of potatoes at ₹ 10/kg. Now, you want to know how much, on average, he paid for the potatoes—the average rate. If you take the arithmetic mean of the two prices then the average rate, the price per kg of potatoes will be ₹ 8/kg. Your father bought 8 kg of potatoes in all. If the average price was ₹ 8/kg he should have paid a total of ₹ 64 (8 X 8). But, he actually paid (6 X 6 + 2 X 10) = ₹ 56. So, where did you go wrong in your calculations?

Let us do the calculation in another way. This time, we first total up how much we paid, ₹ 36 in the first place and ₹ 20 in the second, totalling ₹ 56. Now, divide this by the total kilograms of the potatoes bought, that is 6 kg + 2 kg = 8 kg. So we see that ₹ 56 have been paid for 8 kg of potatoes. Dividing 56 by 8 gives us an average price of ₹ 7/kg.

Coming to the estimation of average speed we should remember that speed is also a rate. Thus, the average speed cannot be arrived at by simply taking the arithmetic mean, the average of various 'speeds'. Rather, you will have to first calculate the total time taken to cover a distance and the total distance covered, and then take the ratio of the two.

**Example 10.** Suppose a car covers 180 km at a uniform speed of 30 km/h, and the next 220 km at a uniform speed of 55 km/h. The average speed will then be calculated in the following way:

$$\text{Total distance traveled} = 180 \text{ km} + 220 \text{ km} = 400 \text{ km}$$

$$\text{Total time taken} = (180 \text{ km} \div 30 \text{ km/h} + 220 \text{ km} \div 55 \text{ km/h})$$

$$= (180 \div 30 + 220 \div 55) \text{ h}$$

$$= (6 + 4) \text{ h} = 10 \text{ h}$$

$$\text{Then, the average speed will be} = (400 \div 10) \text{ km/h} = 40 \text{ km/h}$$

## Speedometer

Vehicle drivers do not carry measuring tapes and stopwatches to measure speed. They just need to look at the watch-like dial of an instrument fitted into the dashboard (Fig. 24). This is called the speedometer. It directly shows the speed in km/h. So, how is speed measured by the speedometer? The wheels of the vehicle have sensors that count the number of rotations completed by the wheels per second. This number, together with the diameter of the wheel is used to estimate the distance covered by the vehicle in a second. The speed is shown in km/h.

Try to look at the speedometers of different vehicles like motorbikes, buses, cars, etc. Do you find any differences between them? Do you think a car's speedometer can be used in an aeroplane?



Fig. 24  
A typical speedometer

**Example 11.** Radhika walks to Shabana's house and from there both of them cycle together to the market to buy a book. After the purchase, Radhika bids goodbye to Shabana and walks back home directly from the shop. Write down some values (with units) for the distances and time intervals involved as shown below in Table 6.

Finally, calculate Radhika's average speed for her entire trip.



Fig. 23 A trip to the market

Table 6

| S.No. | Journey                           | Distance travelled | Time taken | Average Speed |
|-------|-----------------------------------|--------------------|------------|---------------|
| 1     | Radhika's home to Shabana's house |                    |            |               |
| 2     | Shabana's house to the book shop  |                    |            |               |
| 3     | Book shop to Radhika's home       |                    |            |               |

A popular game in villages is to roll a cycle tyre with a stick (Fig. 25). If the tyre has a diameter of 40 cm and makes 10 revolutions per second, what will be its forward speed?



Fig. 25 Sonu on a roll

Hint: In one revolution, the tyre will cover the distance equal to the perimeter of the tyre. The perimeter of a circle is roughly 3.14 times its diameter.

# Crossroads



At this point, there are many ways forward. Depending on the students' background you can go to the section on graphical representation of motion on the next page, or to the discussion of acceleration in one-dimensional motion later on in the module. You can choose to start with any of the two, but we recommend that you discuss both sections. The vector treatment of motion (velocity, etc.) will be discussed in the second module of this series.

# Graphical Representation

## A Picture is Worth a Thousand Words

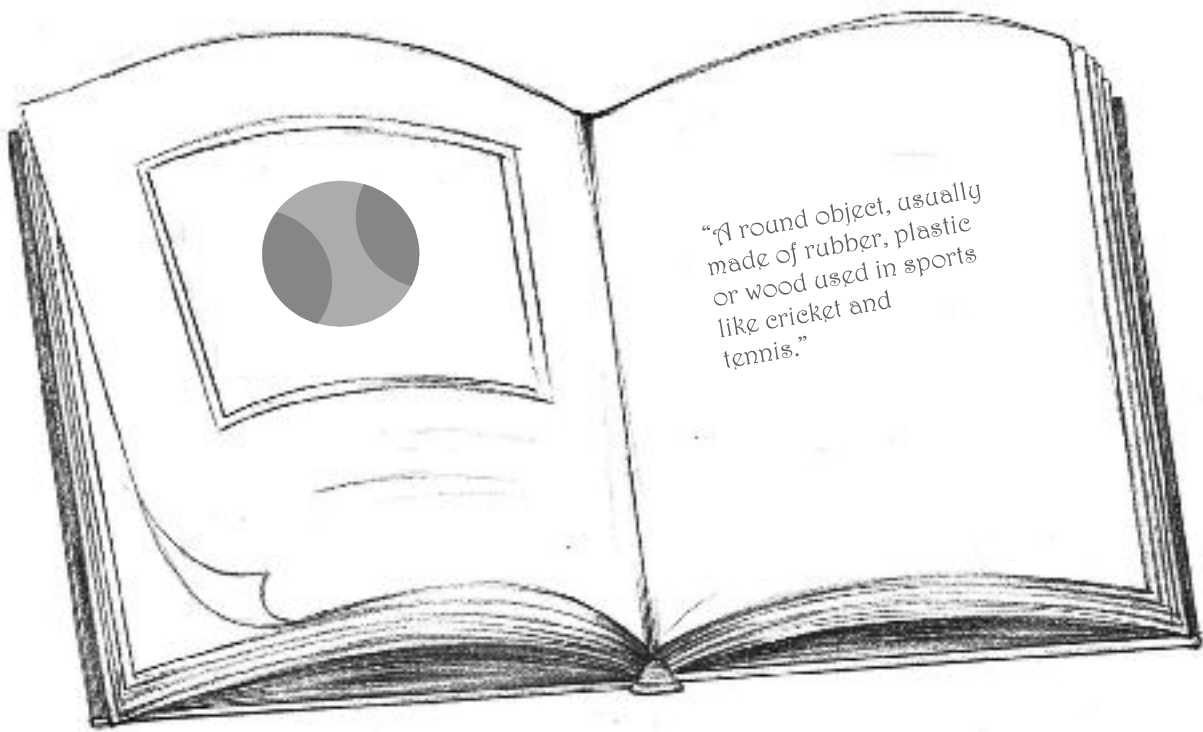


Fig. 26 'B' for ball

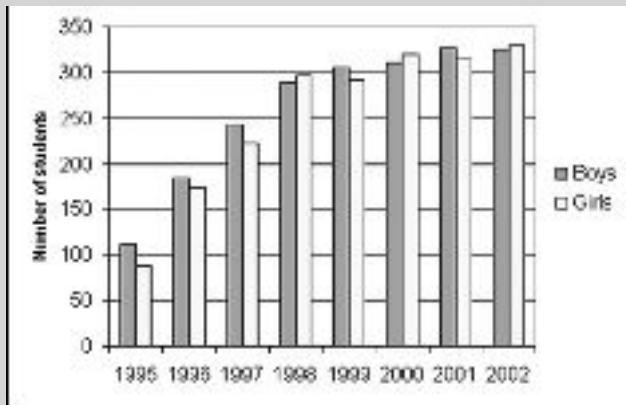
If you had to describe a ball to someone who did not know what it was, which of the above descriptions would you prefer (Fig. 26), the picture on the left or the paragraph on the right?

Pictures are often used to convey information. Graphs are pictures that show numerical data. Have you watched cricket matches on TV? Often, the run rate is shown as a graph. Why do you think it is useful to have data displayed in this form? Do you think graphs can be useful in describing motion as well?

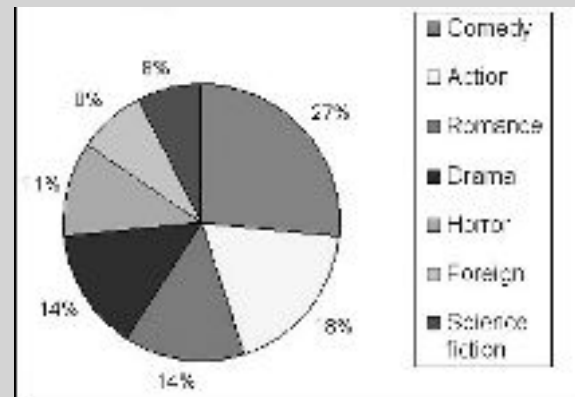
If you are reading about graphs for the first time, we recommend that you first go through Appendix 2 on graphs and then come back to this section.

## Different Graphs - A Sample

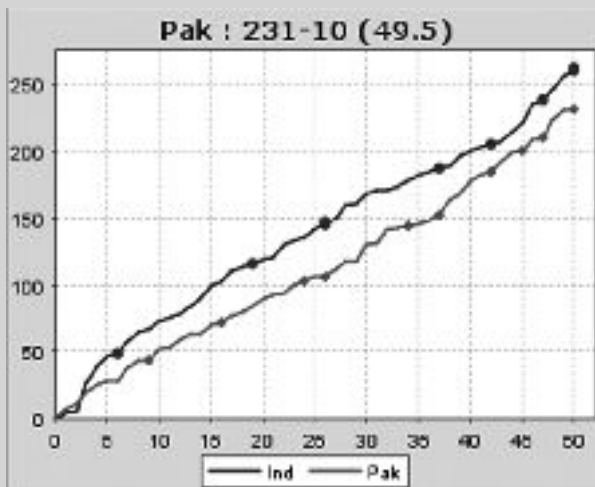
Internet use at a secondary school



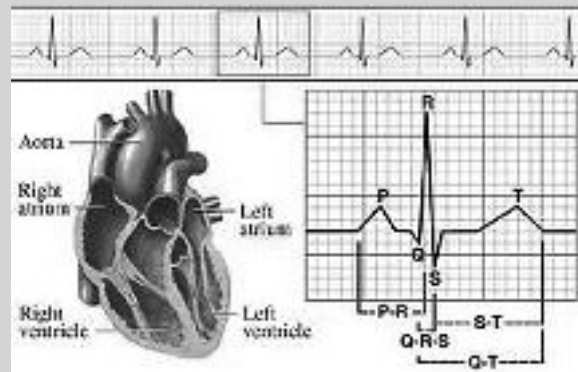
Favourite movie genres in a film class



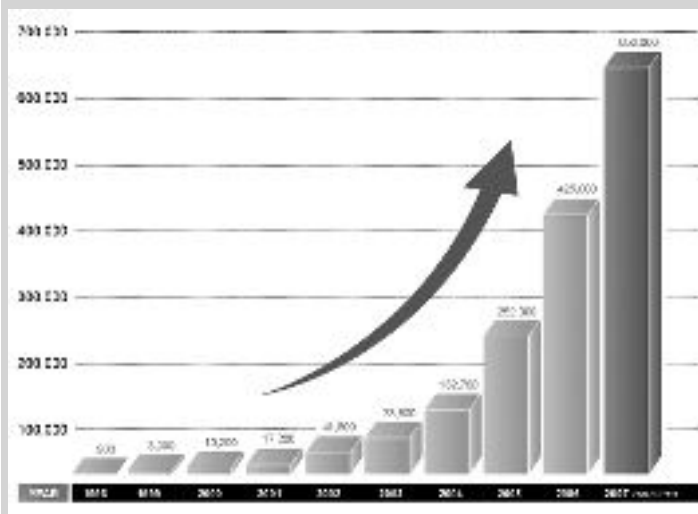
India-Pakistan cricket match score



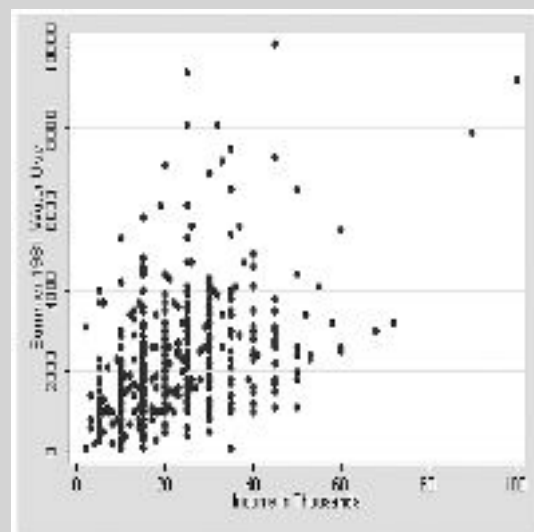
A typical electro-cardiogram (ECG) showing electrical pulses generated by heart muscles



A graph showing a company's growth over a decade



Water usage of different income groups



**Example 12.** Once, my friend Ritu and I visited an old palace that had a large tiled hall. I made Ritu walk slowly in a straight line across the hall. Using a stopwatch, I kept noting down the time at which she crossed each tile. I got the data in Table 7.

What does this table tell me? If I subtract each reading for time by its preceding value, I will know how much time Ritu took to cross that particular tile (Table 8).

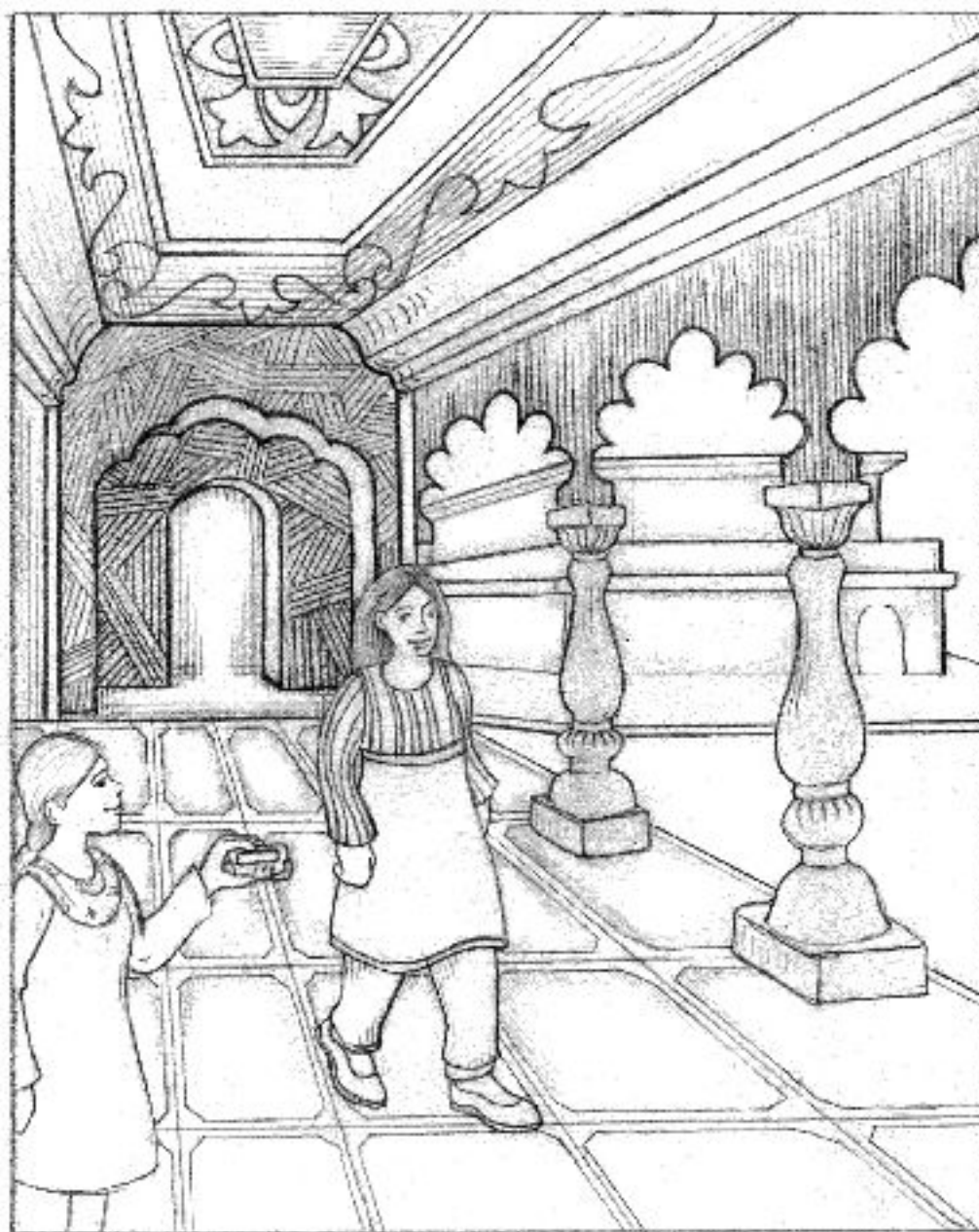


Fig. 28 Ritu and Rehana do an experiment in a palace hall

Table 7

| Tile            | 1    | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12   | 13   | 14   |
|-----------------|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|------|------|
| Distance (in m) | 1    | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12   | 13   | 14   |
| Time (in s)     | 1.25 | 2.4 | 3.4 | 4.2 | 5.0 | 5.7 | 6.5 | 7.3 | 8.0 | 8.8 | 9.6 | 10.4 | 11.3 | 12.6 |

Calculate the average speed for crossing each tile by dividing the length of the tile by the time taken to cross it. What do the results of your calculations tell you about Ritu's motion?

Table 8

| Tile            | 1    | 2    | 3    | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12   | 13   | 14   |
|-----------------|------|------|------|-----|-----|-----|-----|-----|-----|-----|-----|------|------|------|
| Distance (in m) | 1    | 2    | 3    | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12   | 13   | 14   |
| Time (in s)     | 1.25 | 2.4  | 3.4  | 4.2 | 5.0 | 5.7 | 6.5 | 7.3 | 8.0 | 8.8 | 9.6 | 10.4 | 11.3 | 12.6 |
| Time for each   | 1.25 | 1.15 | 1.00 | 0.8 | 0.8 | 0.7 | 0.8 | 0.8 | 0.7 | 0.8 | 0.8 | 0.8  | 0.9  | 1.3  |

Now, I can also plot the data as a graph by putting the tile number on the x-axis and time on the y-axis (Fig.29).

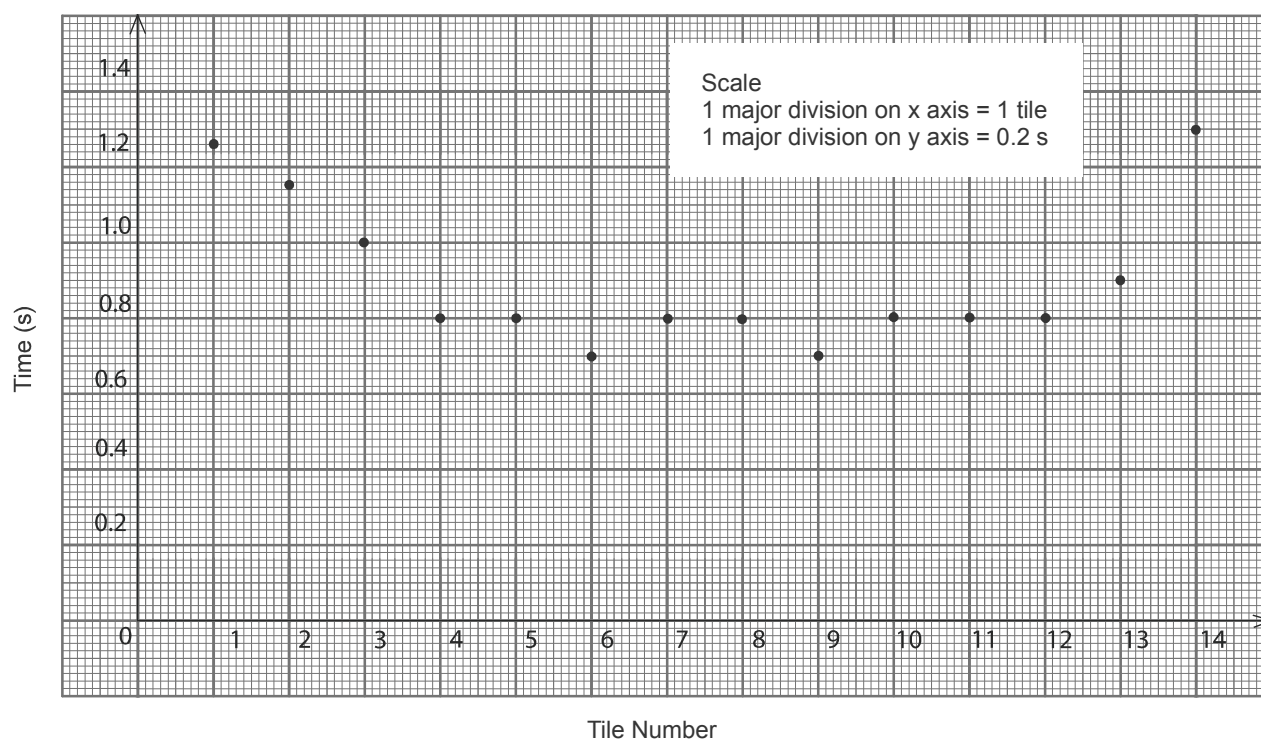


Fig. 29 Time taken to cross each tile



Since I know the length of each tile, I can also plot a time-distance graph (Fig. 30).

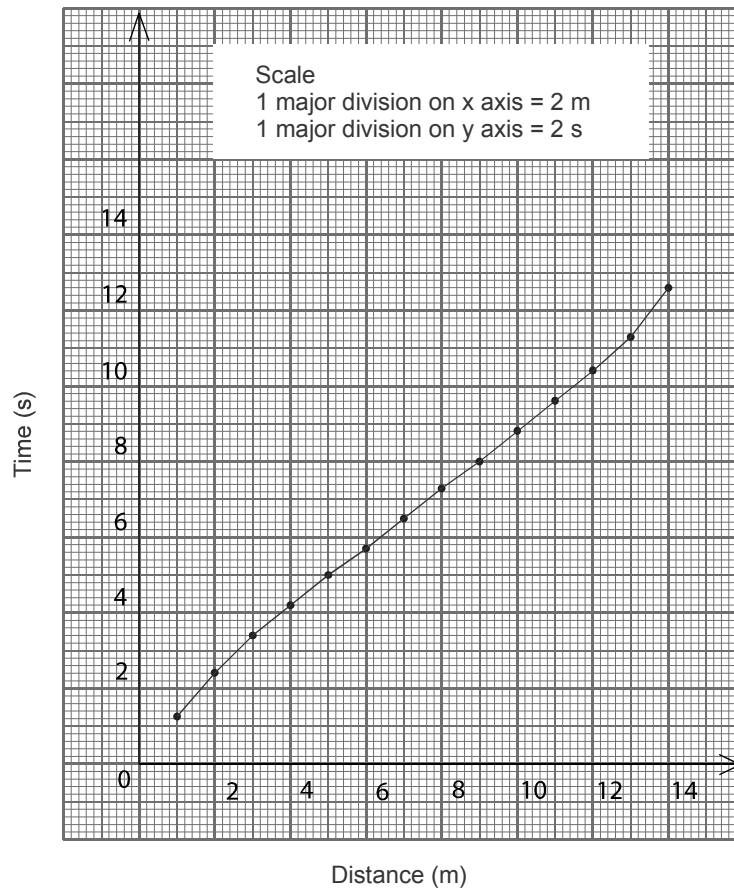


Fig. 30 Total time taken by Ritu to cross the tiles in the hall

A look at the graph straight away tells me that the points do not lie on a single straight line. That means the time taken to cross each tile is different. Had that not been the case (if the time taken to cross each tile was the same for all tiles in the hall), the plotted points would be on a straight line (why?).

A widespread confusion about the interpretation of graphs exists because students think the line of the graph is a drawing of the physical situation the graph describes. For example, looking at the time-distance graph here, some students may imagine that it shows the path actually taken by Ritu. Draw a grid of the tiled floor on paper and ask them to draw what they think is Ritu's path (Fig. 31). Then you can talk about the difference between a graph and a drawing. The actual path represents the positions in space whereas the graph points are measurements of distances between those positions (Fig. 32).

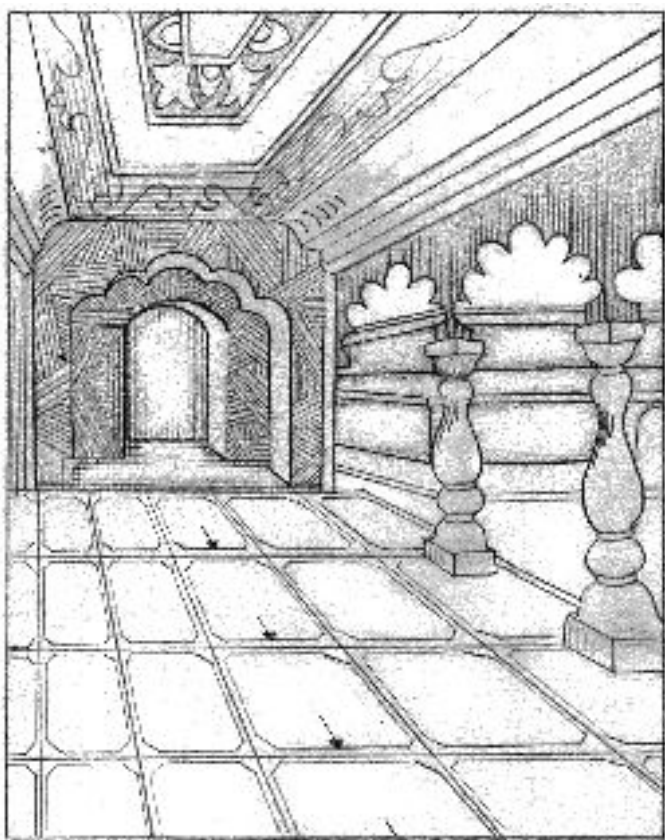


Fig. 31 Ritu's path while walking down the hall

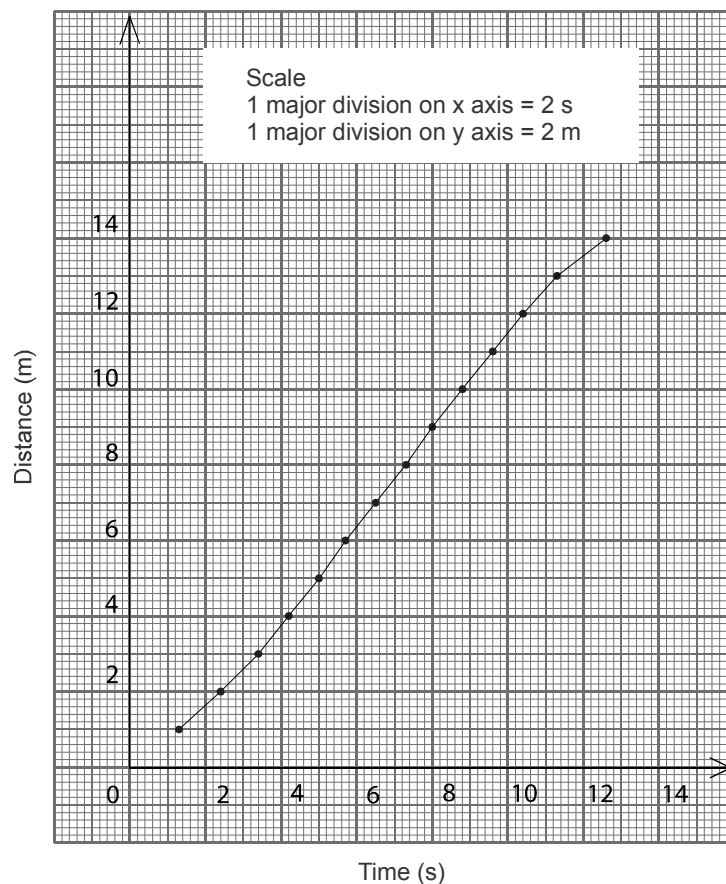


Fig. 32 Distance-time graph of Ritu's motion

Remember, graphs are pictures of numbers, not objects!

**Example 13.** The adjacent Fig. 33 shows several graphs. Time is plotted on the horizontal axis and distance on the vertical axis. The vertical axis shows the position with respect to the starting point. Which of the lines correspond to uniform motion?

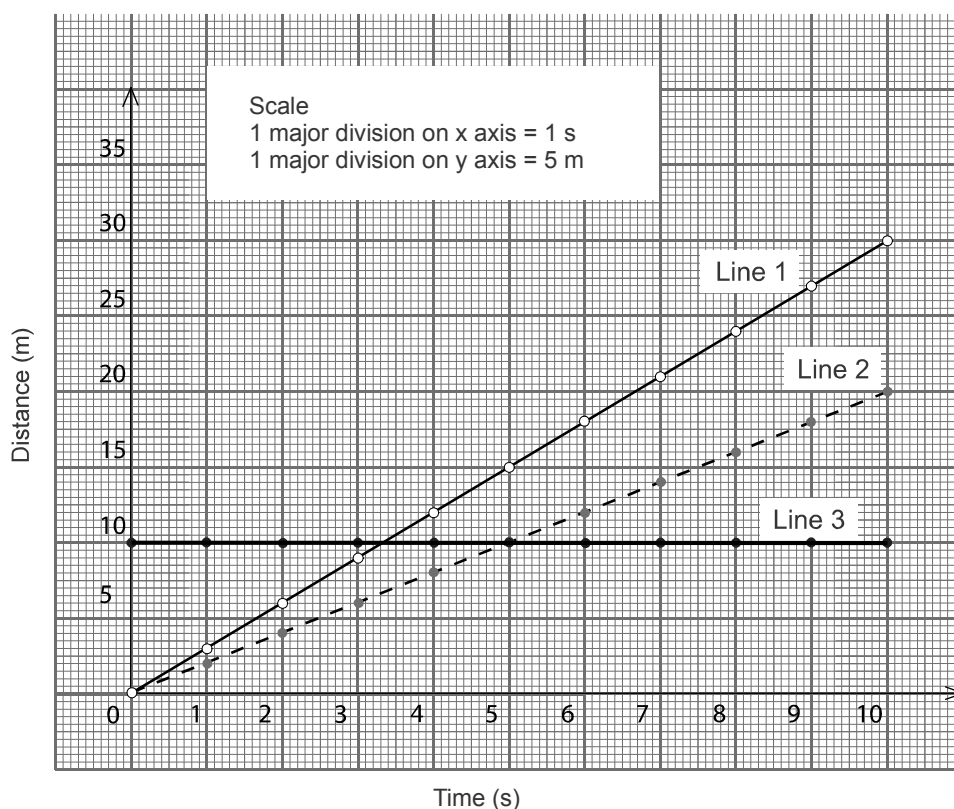


Fig. 33 Distance-time graph showing the position vs. time for three different objects

Let us see what more a distance-time graph can tell us. To begin with, let us look at the graph (Fig. 34) which shows the positions of three cars at different times.

What can we infer from looking at this graph? First, the position of car 3 is constant with time. This means that it remains at one place and is not moving (with respect to the point of reference, of course). So, a horizontal line on a distance-time graph indicates an object at rest.

Next, look at the graph for car 1. The graph for this is also a straight line but it is not horizontal; it is slanted with respect to the axes. Let us read the data points from the graph. Are you able to read the distances corresponding to 30 minutes, 60 minutes and 90 minutes? These distances are 25 km, 50 km and 75 km respectively. If you do a bit of subtraction, you will see that the car moves equal distances in equal time intervals, that is, 25 km every 30 minutes. If we calculate the average speed between any two points, it will come out to be 50 km/h (you have to convert the units for time from min to h). That means car 1 is moving at a uniform speed.

If we do a similar exercise for car 2 we see that it also has a uniform motion but the speed is different from car 1, at 60 km/h. In fact, any straight line on a graph has the property that the ratio of the increment in 'y' values and the increment in 'x' values remains constant. **For a distance-time graph this means the speed is uniform.**

You also see that the line for car 2 is slanted more steeply than that for car 1. It means that the distance covered by car 2 is changing faster. In other words, it has a higher speed. So, **the more steeply slanted a line, higher the speed.** The slant of a straight line is mathematically defined as its **slope** and is calculated as shown in the following box.

The slope of any straight line is the ratio of the change in values on the y-axis to the corresponding change in values on the x-axis. That is, if a value on the x-axis is changed by 10 units and if the

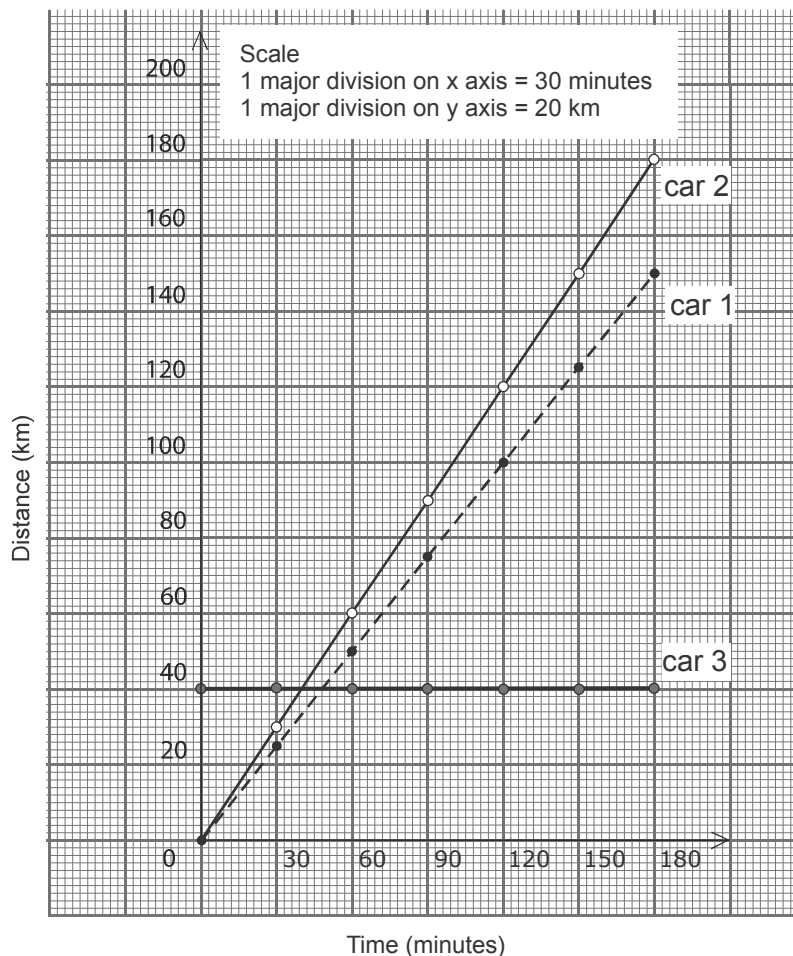


Fig. 34 Distance-time graph showing the position vs. time for three cars

$$\text{Slope of a straight line in a graph} = \frac{\text{Change in y-value}}{\text{Change in x-value}} = \frac{\Delta y}{\Delta x}$$

Here the students should come to the conclusion that if distance-time graph is a straight line, the motion must be uniform. You can plot different sets of imaginary data to confirm this.

corresponding value on the y-axis changes by 20 units, then the slope will be  $20 \div 10 = 2$ . Similarly, in the case of a distance-time graph, the slope of the graph line is the ratio of the change on the distance-axis to the corresponding change in values on the time-axis. This ratio of distance and time is nothing but the average speed. Therefore, we can conclude that **the slope of a distance-time graph is the average speed** of the object whose motion we are studying.

When the distance-time graph is a horizontal line, this line is parallel to the time axis and it makes an angle of zero degrees with it. So, the slope of this horizontal line is zero and therefore, the average speed of the object that the line describes is also zero.

You may ask, when is the distance-time graph not a straight line? Going by the above argument, this will happen if for equal changes in time the distance travelled is different. In terms of speed, this means that at different times the speed is different—the speed is non-uniform. As you may have experienced, most motions that we observe are non-uniform, which is why we can easily get data to plot some of them. The first example we are going to discuss is Rashid's train journey.

Rashid traveled by train from Hoshangabad to Powarkheda. He estimated the distance the train traveled in two-minute intervals by counting the telephone poles along the railway tracks. He noted his estimates in the form of a graph (Fig. 35). This graph describes the motion of the train from the time it left Hoshangabad station until it stopped at Powarkheda station. Read from the graph the distance covered by the train in each two-minute interval and enter the numbers in a table like the one given below.

Table 9

| Time taken (in minutes) | Distance covered (in meters) |
|-------------------------|------------------------------|
| 0-2 (First 2 minutes)   | 100                          |
| 2-4 (Next 2 minutes)    | 400                          |
| 4-6 (.....,.....)       |                              |
| ..... (.....,.....)     |                              |
| ..... (.....,.....)     |                              |
| 20-22 (.....,.....)     |                              |

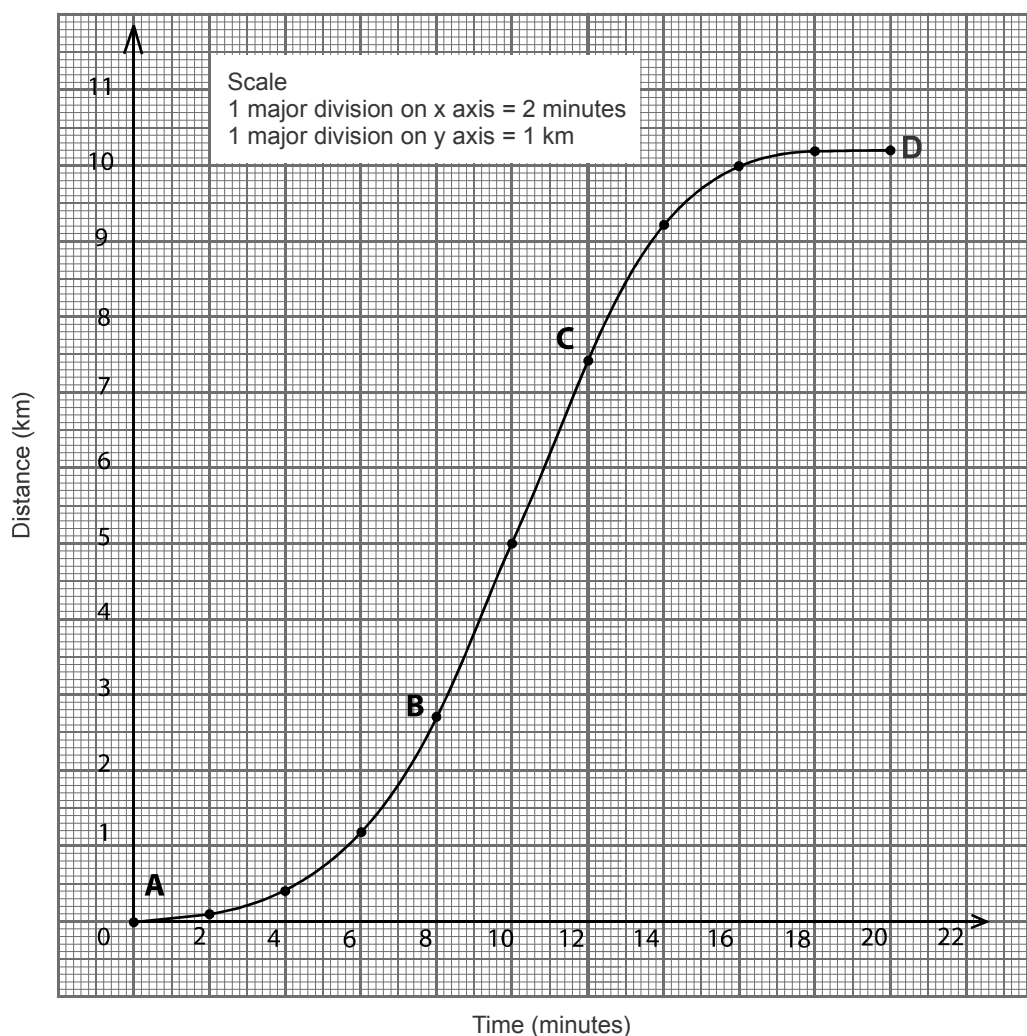


Fig. 35 Distance covered by a train traveling between Hoshangabad and Powarkheda against time taken

Did the train Rashid was traveling in cover equal distances in equal intervals of time? Which sections of the graph show the changing motion, the non-uniform motion of the train? Which sections of the graph show the uniform motion of the train? In which section of the graph is the train stationary?

Look at the sections of non-uniform and uniform motion in the graph. A curve in a graph of motion means the speed of the object is changing continuously in that section. Examine 2-minute sections of the graph. Look at the pattern of average speed in section AB of the graph. The curved line shows a gradual increase in the train's speed as it leaves Hoshangabad station. In section BC, where we have a straight line, the speed remains the same throughout that section. Further, in section CD, we find a curve again and if we analyse it in 2-minute segments, we find that the speed is not constant in that section. In fact, it shows a decreasing pattern.

1. What is the average speed of the train from  $t = 0$  minutes to  $t = 6$  minutes?

2. What is the average speed of the train from  $t = 4$  minutes to  $t = 14$  minutes?

So far, we have calculated the slope as the distance traveled in a given time interval and thus estimated the average speed for that time segment. Can one also find out the instantaneous speed of motion from the graph? If you remember, instantaneous speed is the speed over the smallest measurable time interval.

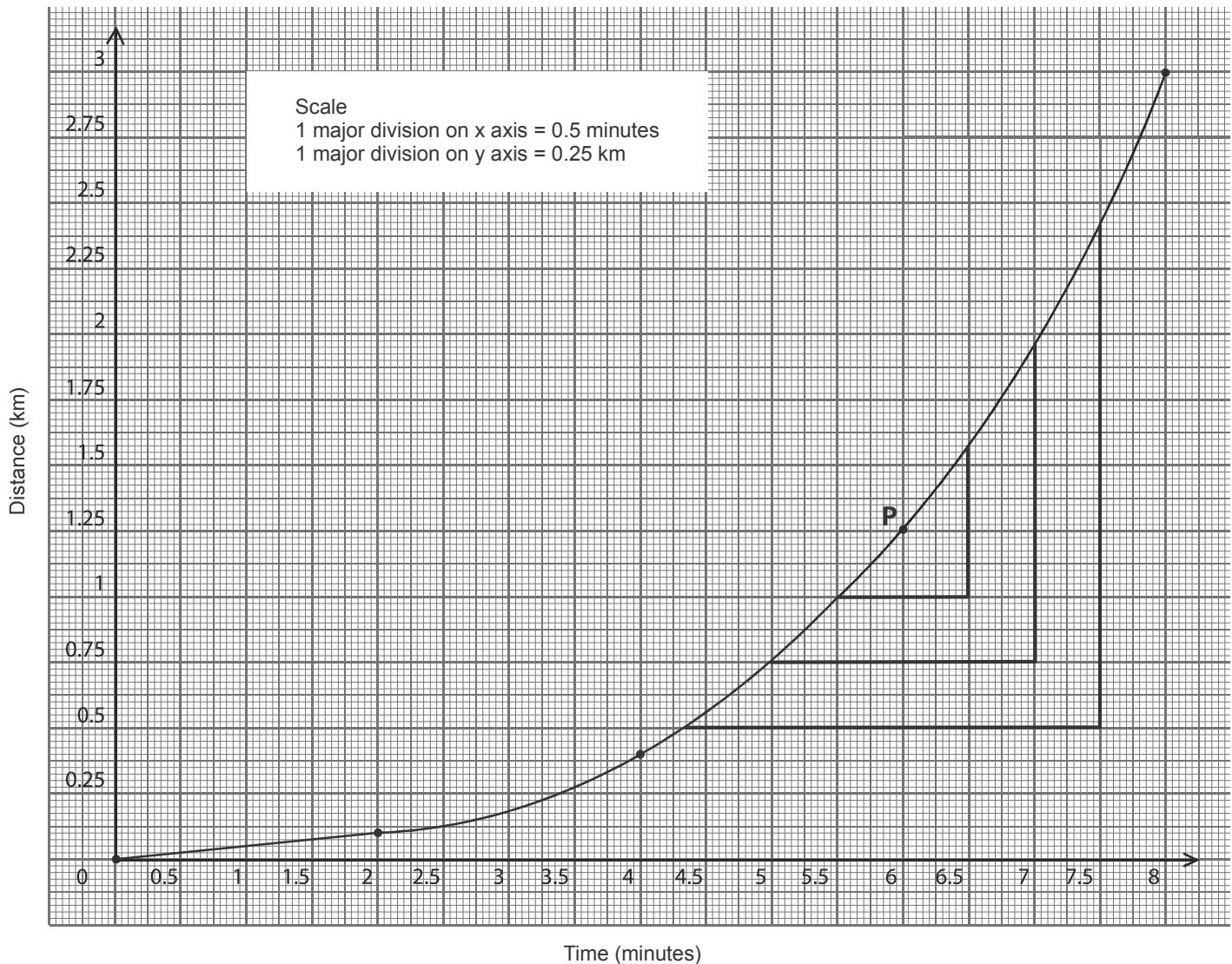


Fig. 36 Calculating the slope for a distance-time graph to find the instantaneous speed

Applying that definition here, we can reduce the time interval to a sufficiently small value and calculate the slope. Time  $t = 6$  minutes corresponds to the point P on the graph.

Figure 36 shows three segments from one side of point P to the other, each a neighbourhood. As we go closer and closer to point P, the straight line joining the two ends of a neighbourhood starts overlapping with the curve itself. Can you safely assume that in the segment of the curve from  $t = 5.5$  minutes to  $t = 6.5$  minutes, the average speed is the same as the slope of the straight line joining the two graph points in this neighbourhood? We can take the slope of the straight line and call it the speed at its

midpoint, the speed at  $t = 6$  minutes, or 'the instantaneous speed' at  $t = 6$  minutes. Thus, the instantaneous speed at a particular instant can be equated to the average speed of a particular time interval, provided:

1. The particular instant is included in that time interval.
2. The slope of the line joining the end points of the neighbourhood is obtained for a small enough part of the curve, one which is nearly a straight line segment so that it does not change appreciably when we compute it over a still smaller time interval.

If the segment length is made infinitely small (such that the segment can be taken to be almost a point), the straight line corresponding to its slope is called a 'tangent' at that point of the curve.

Now, you may like to go back and estimate Rashid's speed at  $t = 6, 12$  and  $18$  minutes.

Suppose you get the distance-time graph of a rolling ball on an inclined plane similar to Fig. 37, can you say by just looking at the graph whether its speed is increasing, decreasing or constant?

Try and draw a few tangents at different points in this graph. Remember, we have just discussed that tangents can replace the straight lines joining the ends of very small neighbourhoods. Compare the slopes of these lines. The tangent passing through point A is tilted more towards the x-axis, compared with the tangent at point B, and so on. You find that the slope is increasing continuously from point A to point B to point C, and so on. It means the instantaneous speed, which is interpreted as the slope of these tangents, is also continuously increasing.

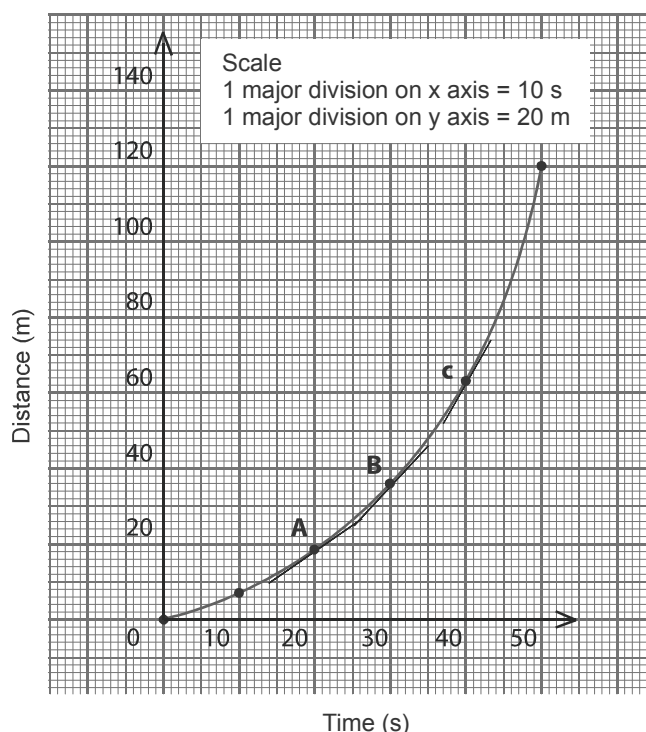


Fig. 37 Finding the slope at different points on a distance-time graph to interpret non-uniform motion

At the same time, if you draw a distance-time graph of the motion of a car as its brakes are being applied, you will find that the slopes at different points of the graph keep decreasing with time and so you can say that the speed is decreasing (Fig. 38).

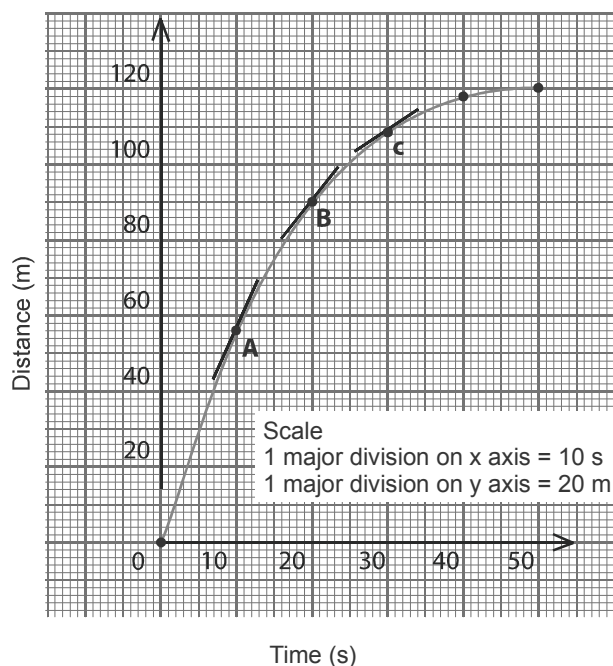


Fig. 38 Finding the slope at different points on a distance-time graph of a car after its brakes have been applied

Looking at the graphs of non-uniform motion and the effort required to extract information about the changing speeds from them, it may be better to directly plot a speed versus time graph.

In a speed-time graph, conventionally, instantaneous speed is shown on the vertical axis and time is shown on the horizontal axis. Table 10 lists data on the positions and speeds of a freely falling body at different points in time. Figs. 39 and 40 show the distance-time and the speed-time graphs, respectively, for this data.

Table 10

| Data Point | Time (s) | Distance from the starting point (m) | Instantaneous speed (m/s) |
|------------|----------|--------------------------------------|---------------------------|
| 1          | 1        | 5                                    | 10                        |
| 2          | 2        | 20                                   | 20                        |
| 3          | 3        | 45                                   | 30                        |
| 4          | 4        | 80                                   | 40                        |
| 5          | 5        | 125                                  | 50                        |



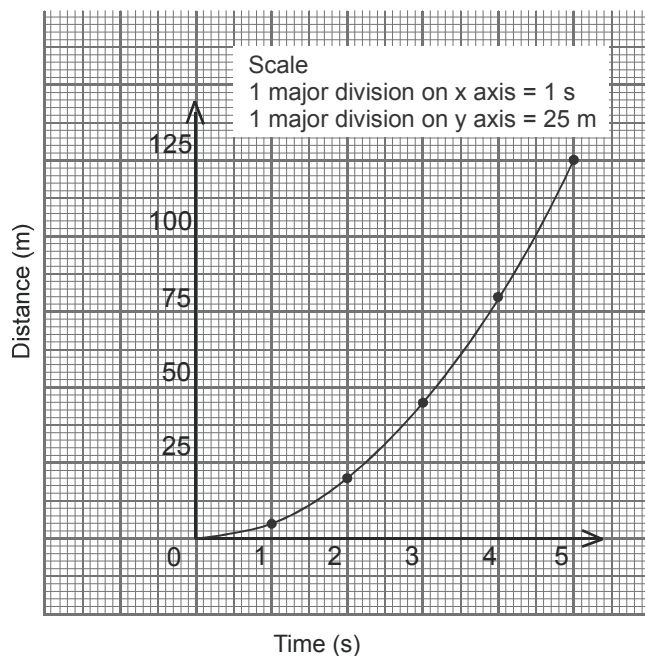


Fig. 39 Distance-time graph showing non-uniform motion

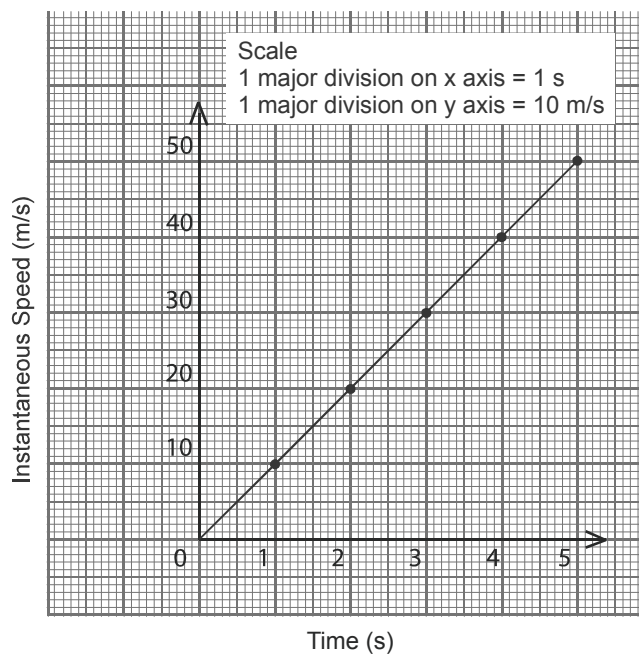


Fig. 40 Instantaneous speed-time graph showing the same non-uniform motion

If you want to further explore the graphical representation of motion, you can use the material given in Appendix 2. Showing the students two graphs with different speed-time behaviours is one way to introduce acceleration. However, if you do not want to use graphs, you can go straight to the section that begins on the following page after the discussion on average speed.

# Acceleration in One-Dimensional Motion



What is the difference between a racing car and one that you normally see in everyday traffic? One difference is that the racing vehicle has a higher top speed.

Another important difference is that a racing car has a higher pick-up. What does the word 'pick-up' mean (remember the ad slogan "0 to 60 in 8 s")? It tells you how fast a vehicle can increase its speed. This is one way of measuring the non-uniformity of motion. The technical term for it is 'acceleration'.

Acceleration (for motion in a single dimension) can be defined mathematically by the following relationship:

$$\text{Magnitude of Acceleration (a)} = \frac{\text{Final speed (v) - Initial speed (u)}}{\text{Time over which this speed change is measured (t)}}$$

\*

Suppose a bus is moving at a speed of 30 km/h, and the speed is then increased in one minute to 50 km/h. The acceleration of the bus is calculated in the following way:

$$\text{Change in speed} = 50 \text{ km/h} - 30 \text{ km/h} = 20 \text{ km/h}$$

$$\text{Time taken for this change} = 1 \text{ min}$$

$$\text{Magnitude of acceleration} = 20 \text{ km/h} / 1 \text{ min} = 20 \text{ km/h} / 1/60 \text{ h} = 1200 \text{ km/h}^2$$

Note that we converted the time taken from minutes to hours. If we had not done so, the acceleration would have been 20 km/ h.min. Both the units are equally valid but conventionally, the former is used.

If the bus slows down to 10 km/h in 1 min (from the same initial speed) then its acceleration is:

$$\text{Magnitude of acceleration} = (10 \text{ km/h} - 30 \text{ km/h}) / 1/60 \text{ h} = -20 \text{ km/h} / 1/60 \text{ h} = -1200 \text{ km/h}^2$$

---

\* 'a', 'u', 'v' and 't' are standard symbols.

The acceleration is negative now. Negative acceleration is also called 'retardation' or 'deceleration'. Thus, a positive value for acceleration indicates an increase in speed with time whereas a negative value means a decrease in speed with time. A higher value of deceleration means that the moving object can be stopped in a shorter time. This also means that it will come to a stop over a shorter distance.

Why must you maintain a larger distance behind a vehicle with a 'power brake'?

At this stage it may be helpful to do an activity where accelerated motion can be observed. You can start by posing the problem of measuring the motion of a falling stone. In line with earlier measurements made by the students, they may suggest using a stopwatch and making marks on a wall to measure the speed of the stone at various points during its fall. You will find that the time taken by the stone to fall to the ground is too short to be measured accurately by a stopwatch. Someone might suggest going up on the roof and dropping the stone from there. Try all possible methods. If the measurements are difficult to make, ask the students to think whether the motion (speed) of a falling stone is uniform or not, and why. All non-uniform motion involves acceleration.

Once the students have reached the conclusion that it is not possible to measure the time of a freely falling object using ordinary stopwatches, lead the discussion onto how to get around this problem. One way is to use instruments that can measure faster. Such devices, like electronic stopwatches can measure smaller intervals of time. The other way is to somehow slow down the fall of the object. Discuss the various ways in which this can be done. One could be to make it fall in a liquid column. Another way could be to move the object down a plane inclined at some angle other than the vertical. Galileo used this method to arrive at his theory of motion and inertia. His innovation was to increase the time of fall by using an inclined plane and rolling a ball on it.

Galileo pointed out that the nature of motion in both these cases (free fall as well as motion on an inclined plane) is the same because the governing forces are similar. The forces acting on a ball rolling down an inclined plane are gravity and the friction offered by the plane. We will discuss them in detail in the second module of this series. Similarly, in a free fall, a body falls under the influence of forces due to gravity and air resistance. So, the difference between the nature of motion in both these cases is only in the magnitudes of these forces. The vertical free fall is actually a limiting case of the motion along an inclined plane and the vertical plane can be taken as an inclined plane kept at an angle of 90 degrees.

The following activity can be done either as a demonstration by the teacher or by students in groups of 4 or 5. It requires minimal equipment which can be easily procured in most schools. This is also the point where we take up an example of motion in a vertical direction, although it is still in a single dimension. This will hopefully prevent the students from thinking that motion in one dimension means only in the horizontal plane (a widely held misconception).

During this activity, you may get a chance to address a widespread confusion between speed and acceleration. Try to emphasise that these are entirely different quantities. An object may be moving at a very high speed with zero acceleration, whereas another may be moving very slowly but with a very large acceleration. For example, consider a car starting as the signal turns from red to green. Its initial speed is zero but its acceleration is large. After it has crossed the signal and reached the highway, the car's speed is quite high but its acceleration may be close to zero.

## Modern Galileos

Let us now try to do some measurements on an accelerating object. This activity is inspired by a landmark experiment done by the famous scientist Galileo in the 17th century. All you need to do is to arrange a plank, a ball to roll on it, a scale to measure distance and a stopwatch to measure time intervals. You can use the back of a blackboard, table-tops or classroom desks as planks for this activity. Make sure that the plank is more or less flat, without dents and is at least 1 meter long (it will be difficult to take the readings if the plank is any shorter). Divide the plank into two equal segments of 45 cm by drawing lines across its width. Also mark a small line 3-4 cm before the first line. This will be the mark for releasing the ball (Fig. 41). Now, keep the plank on the floor or a flat table and raise one end by 3-4 cm. The plank will then be inclined at an angle of about two degrees to the horizontal. The accompanying pictures show one such arrangement with two segments marked on a plank. You can use small rubber or plastic balls, or even glass marbles for rolling down the inclined plane. The experiment consists of rolling

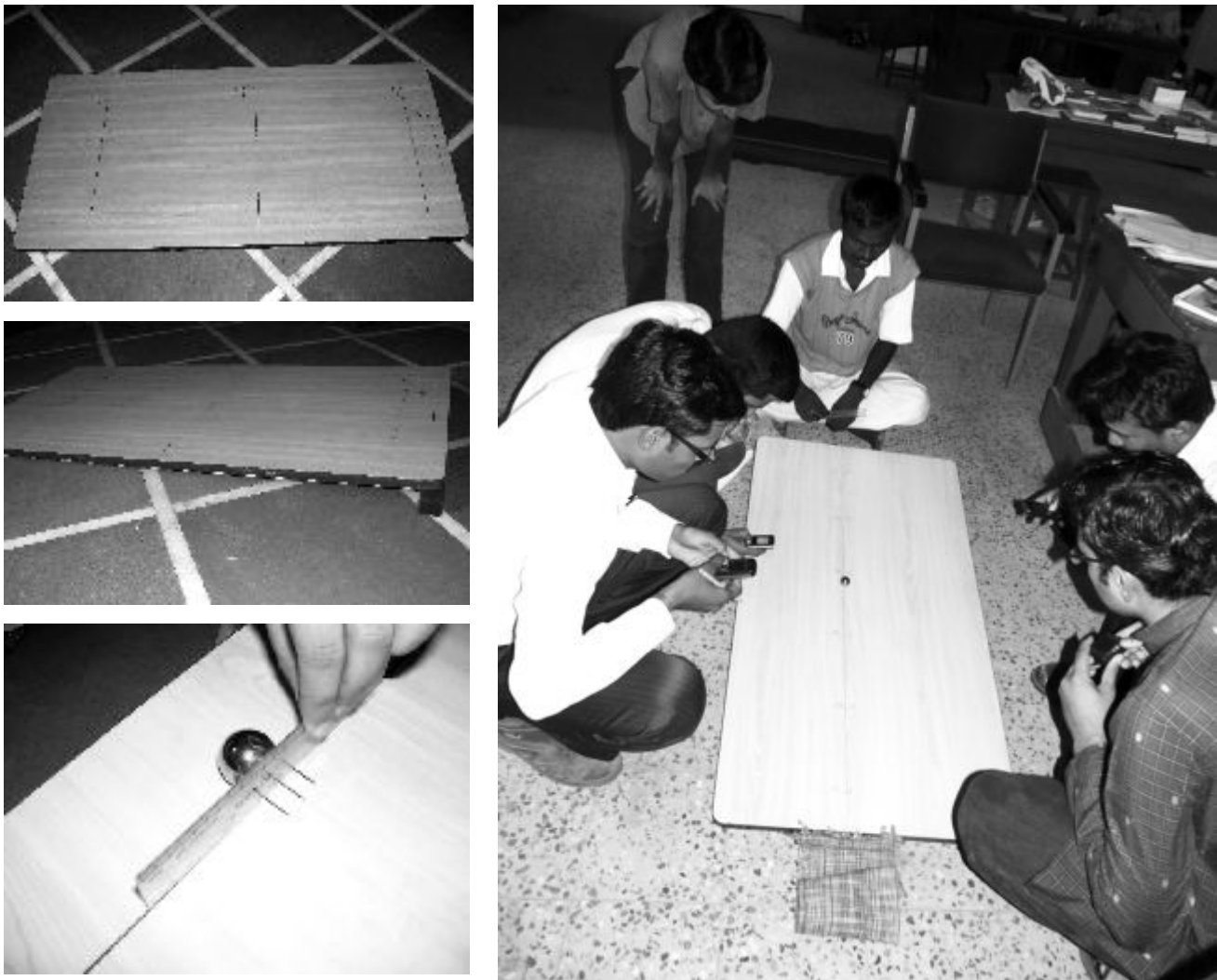


Fig. 41 A group of teachers doing the inclined plane activity. The picture on the bottom left shows a ruler to keep the ball at the starting point. When the ruler is removed, the ball starts rolling from this fixed starting place and with minimum starting speed.

the ball down the inclined plank and measuring the time it takes to cross each segment. For this, assign one person with a stopwatch to each segment. A third person starts the ball rolling by releasing it at the starting line. The time taken for the ball to cross each segment is noted down in a table similar to the one given below (Table 11). Once the time to cross each segment has been noted down, the average speed in each segment can be calculated by dividing the segment length by the time taken.

Like in any experiment, some precautions need to be taken to get reliable data. Firstly, the starting point should be the same in each trial. For example, in the bottom left picture of Fig. 41, three small lines can be seen drawn perpendicular to the starting line. These are to ensure that the ball is always released from the same place. The starting point should be selected by rolling the ball down the plane from various points along the starting line, and selecting the spot from where the ball rolls straight down the plank and does not veer to the sides. Ensuring that the starting point is the same takes care of any difference between trials arising due to warps, dents or scratches on the plank. In this way we try to minimise systematic errors. For more details on systematic errors and the ways in which they can be avoided, refer to appendix 3.

Secondly, care should be taken that the ball is not given an initial push when being released, that is, it must be released from a stationary position. This can be done with some practice. Using a ruler to hold the ball in place and releasing the ball by lifting the ruler off the board also works well. Thirdly, the experiment should be repeated several times. This is to get an estimate of the random error.

Table 11

Segment Length: \_\_\_\_\_ cm

Material of the ball: \_\_\_\_\_

Tilt given to the plank: \_\_\_\_\_ degrees

| Segment no. | Time taken to cross the segment(s) | Average speed in the segment (m/s) |
|-------------|------------------------------------|------------------------------------|
| First       |                                    |                                    |
| Second      |                                    |                                    |

Alternatively, the readings can also be taken as follows: one student notes the time taken for the ball to cross the first segment, and another notes the time taken for the ball to cross two segments. The time taken to cross each segment can then be calculated from the two values.

You can divide the plank into three segments and repeat the experiment. You can do this if the plank is long enough and the students become skillful in using the stopwatch to get accurate values for time.

Table 12

| Segment no. | Time taken to cross the segment(s) | Average speed in the segment (m/s) |
|-------------|------------------------------------|------------------------------------|
| 1           | 2.72                               | 0.18                               |
| 2           | 1.89                               | 0.25                               |
| 3           | 1.51                               | 0.32                               |
| 4           | 1.33                               | 0.36                               |
| 5           | 1.15                               | 0.42                               |
| 6           | 0.93                               | 0.52                               |

Table 12 shows the data from such an experiment done with a much longer aluminium plank during a training workshop. The plank was divided into six segments of 48 cm each.

### Analysis:

1. Look at the second column of Table 12. The time taken to cross each segment decreases continuously as the ball progresses down the plank. Since the segments are all of the same length, this means the ball moves faster in the later segments. Based on the definitions of speed and acceleration we arrived at earlier, we deduce that the ball is undergoing accelerated motion and that this acceleration is positive.
2. The average speeds calculated in the third column of Table 12 show that the average speed increases as the ball moves down. Now, we can imagine what would have happened if the plank had been divided into more segments. The same length could have been divided into 9 segments. Then too we would have found the average speed for each segment to be higher than that for the preceding segment. Subdividing the segments like this (in our imagination), we can

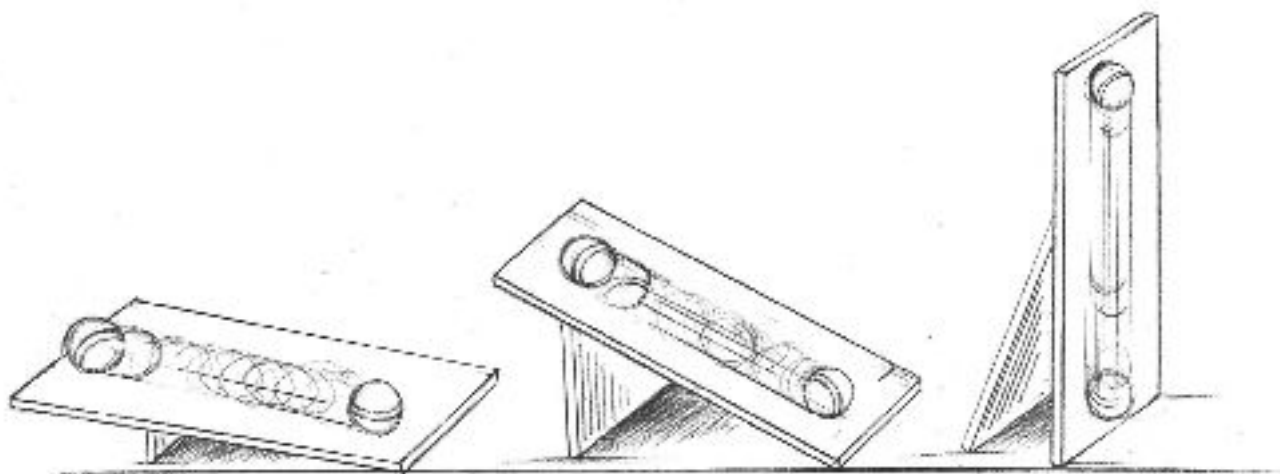


Fig. 42 Ball rolling down the planks inclined at various angles, including the vertical.

argue that the instantaneous speed (i.e. the average speed measured over the smallest time interval) increases continuously as the ball rolls down the plank.

3. Change the angle of the plank and repeat the experiment (Fig. 42). You will find that although the times to cross the segments change, the time taken by the ball to cross the second segment is always less than the time taken to cross the first. This will hold true even if the plank is held vertical, a situation equivalent to dropping a ball in air, that is, free fall. Thus, we can conclude that free fall is also accelerated motion.

Imagine trying to measure the acceleration of, say, an ant, or someone taking a walk, a rolling ball or a stone thrown in the air. Discuss amongst yourselves the best way to do this.

## Acceleration Around Us

Which do you think has a higher speed—a giant wheel in a *mela* or a Shatabdi Express train? If you guessed the Shatabdi, then you are right. The average speed of a Shatabdi Express train is nearly 10 times that of a typical giant wheel. Yet, the thrill you get on a giant wheel is absent while seated in the air-conditioned comfort of this train. One reason may be that a person sitting in a uniformly moving train feels almost no acceleration, whereas in a giant wheel the acceleration can be as much as 1.5 times that felt by a freely falling stone. But even in the train, we can feel the change in motion when the train is speeding up, slowing down or turning along a curve. This change in motion can be felt more starkly when traveling in a bus; when the driver brakes suddenly, the jerk we feel is the (negative) acceleration of the bus coming to a stop.

In a giant wheel, we experience forces in different directions when we are at the top, the middle and the bottom of the ride. Along with this, the sensation of moving up and down adds to the thrill. We will learn more about the action of force on motion in part 2 of this series of modules.

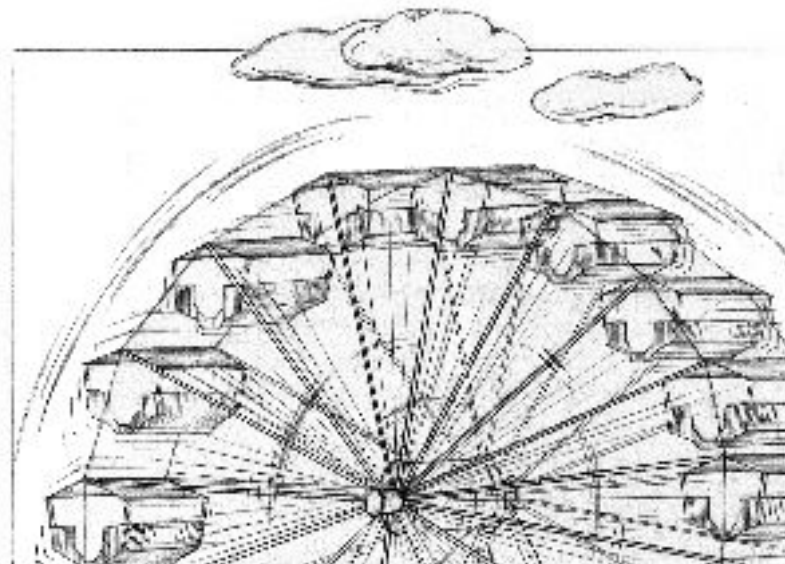


Fig. 43 Various positions in a giant wheel

Some typical values for acceleration are shown in Table 13:

Table 13

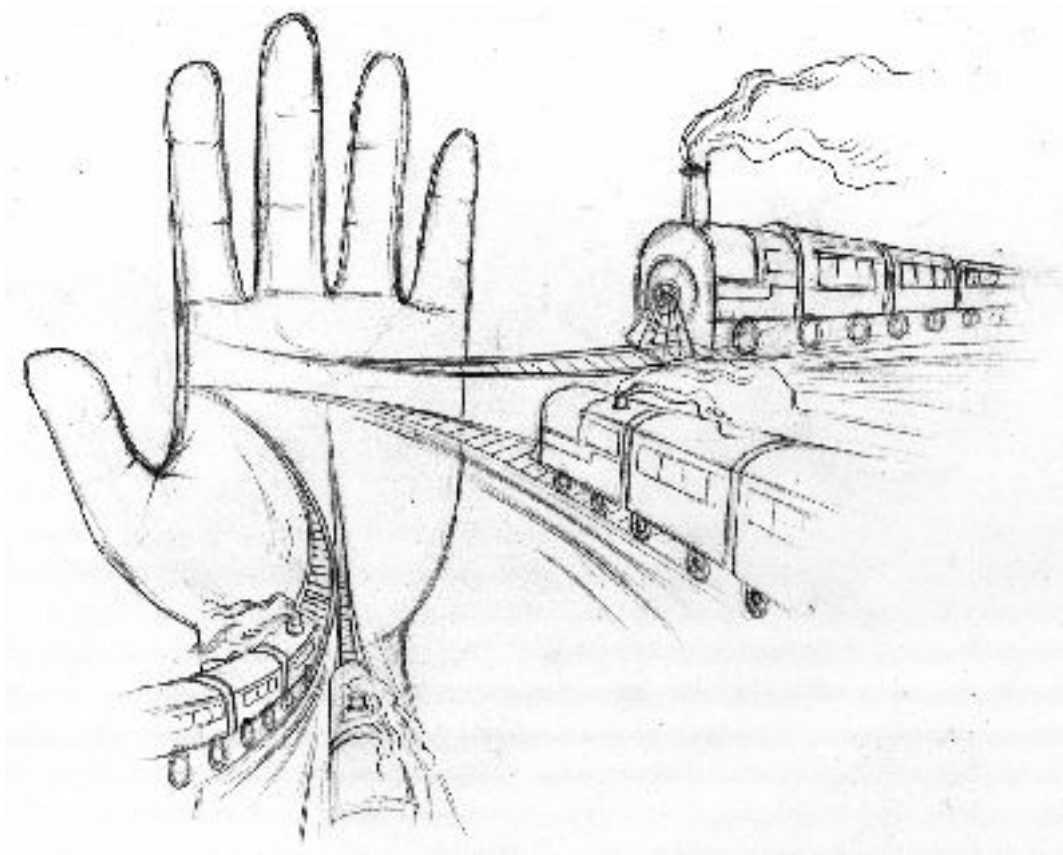
| Sl. No. | Motion                              | Typical acceleration ( $\text{m/s}^2$ ) |
|---------|-------------------------------------|-----------------------------------------|
| 1       | Falling stone (free fall, on Earth) | 9.8                                     |
| 2       | Falling stone (on the Moon)         | 1.6                                     |
| 3       | Lift in a shopping mall             | 1                                       |
| 4       | Bullet shot out of a gun            | 1,00,000                                |
| 5       | Pick-up of a family car             | 3                                       |
| 6       | Pick-up of a racing car             | 170                                     |

## Is There an Accelerometer?

You might be wondering if, like the speedometer, vehicles also have an instrument that measures and displays acceleration. The answer is 'no', there is no such instrument on normal vehicles. The reasons probably are, (a) in the normal course of driving, information about speed is sufficient for the driver, and (b) as you have seen, it is much more complicated to measure acceleration. However, there are instruments called accelerometers available and you will see them if you visit a car factory. They are used in testing the performance of engines as well as brakes. Accelerometers are also used to measure vibrations in cars, machines, buildings, process control systems and safety installations. Specifically configured accelerometers called gravimeters are used to measure changes in gravity. Accelerometers are now being used to track the movements of animals, in sports training, rockets and video games. They can also be seen in the latest mobile phones.



# Predicting Motion



Until now we have described motion in two ways: one, by giving values of the measured position or speed at different times, and the other showing the same information graphically. So far, so good. But we have to remember that one aim of science is also to predict how any process is going to evolve with time, if the initial conditions are known. Coming to the question of where we would need to use the calculations of motion, just think of our vast railway network. How would we coordinate the running of trains on the same track if we could not calculate the position of a moving train at different times? Can you think of some more examples?

By this time the students would have got some familiarity in quantifying the motion of phenomena which they observe all around them. Now, they can be introduced to the correspondence of a physical process to an appropriate mathematical equation, another powerful tool used by science. These equations are, for the moment, described in the scalar form for one-dimensional motion.

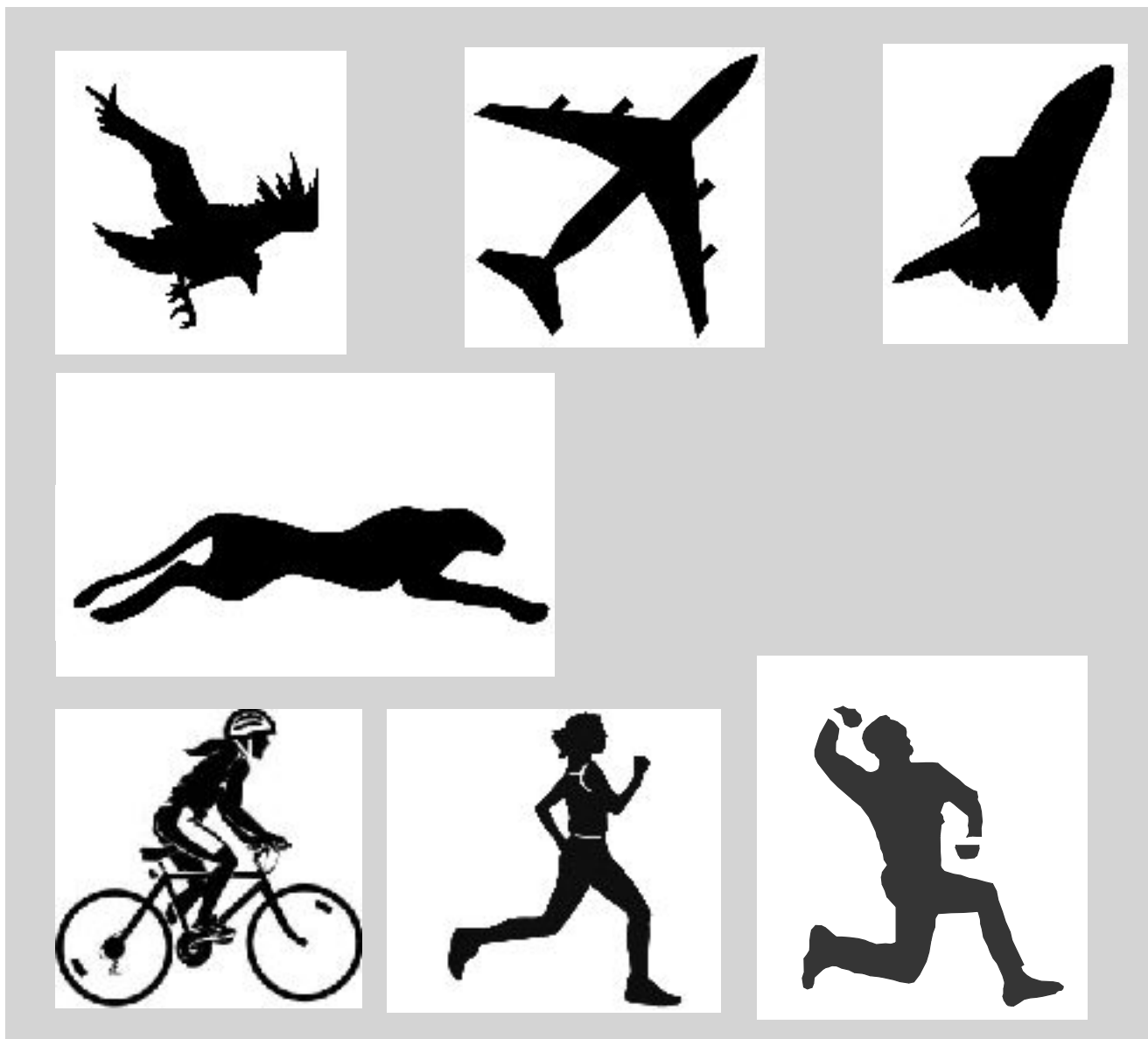


Fig. 44 Various moving objects

To take a specific case, a bus is traveling in a certain direction at a uniform speed of 40 km/h. Can we tell how far the bus will have traveled in six and a half hours if it kept to the same speed? Or, a bus is moving at a speed of 20 km/h and is given an acceleration of  $120 \text{ km/h}^2$  in the same direction. Can we predict what its speed will be after 30 minutes? Conversely, can we find out how much time will it take to increase the speed of the bus to 60 km/h?

To answer such questions, science uses another tool, which is the mathematical representation of objects, properties and physical processes. We have already seen that we can define and measure some properties of linear motion, namely distance, time, speed and acceleration. Now we shall see how to mathematically define the relations between these quantities. Such relations are nothing but equations connecting the various mathematical quantities.

In describing acceleration earlier on page 49, we had written the following equation:

$$a = (v - u) \div t$$

where 'u' is the initial speed, 'v' the final speed, 't' the time taken to change the speed and 'a' the acceleration. These terms can be rearranged to get the more popular form:

$$v = u + at$$

which is also known as the **first equation of motion**.

If an object has **constant acceleration**, then we know from the above discussion that its speed changes linearly with time (Fig. 40 on page 48). In this case, the average speed is equal to  $(u + v) / 2$ . A general proof of this is beyond the scope of this module, but do remember this averaging works **only if acceleration is constant**. We know from our prior discussion that the average speed = distance covered / time taken. If we denote distance by 's', then we can write:

$$(u + v) \div 2 = s \div t$$

This can be rewritten as:

$$s = (u + v) \times t \div 2$$

Substituting for v from first equation of motion, we get:

$$s = (u + u + at) \times t \div 2$$

$$s = ut + at^2 \div 2$$

which is also known as the **second equation of motion**.

We can also combine the above two equations to get a third relationship in terms of only 'v', 'u', 's' and 'a'.

From the first equation,

$$v = u + at$$

giving

$$t = (v - u) \div a$$

And from second equation of motion,

$$s = ut + \frac{1}{2}at^2$$

Substituting for 't' in the second equation, we get:

$$s = u (v - u) \div a + \frac{1}{2}a (v - u)^2 \div a^2$$

Then the equation can be simplified (try to do this yourself) to the following, more common form:

$$v^2 = u^2 + 2as$$

which is also known as the **third equation of motion**.

If the motion of an object is retarded, you will have to take '-a' as the magnitude of a.

At this point students should be made to do some problems using these equations. Standard textbook problems deal with the movements of balls, stones and vehicles which may seem a little artificial to them. To kindle their interest, two projects are given below. After working on the projects they can be asked to do some of the problems from the problem set.

For the projects, the students have to make a written schedule which can be displayed on the wall like a poster. They can make it attractive by putting in drawings and pictures as well. You can also make up more such examples and hold a competition between different groups. These projects will give them some practice in doing calculations using the equations of motion.

From here they can go on to do the more conventional problems given in appendix 5.

### Project 1: Shakkarpara Express

Remember our vast railway network? The railway timetable is made by calculating how much time each train will take between two stations, how much time-gap there should be between two trains on the same track, etc. All these calculations use the very same relationships that we have been discussing. If you like, you can also try your hand at designing an imaginary rail network.

In the times of the Rajas, the different Indian kingdoms had each their own separate railway network. Let us imagine a small but rich *jagir* with three villages. The *jagirdar*, Seth Shakarkand, lives in Shakkarpara, grows sugarcane in Gannaganj, and the sugar mill is in the third village, Milleria. The *jagirdar* wants a railway to travel between the villages and transport sugarcane to the mill. He calls his engineer and tells him to make the train schedule for the sugarcane season:

1. Shakarkand's supervisor and some more employees have to go from Shakkarpara in the morning to reach Gannaganj by 8 a.m and Milleria before 9 a.m.
2. Shakkarkand wants to go around mid-day to Gannaganj, spend two hours there, then go to Milleria, spend two hours there and then come back.
3. Loading sugarcane onto the train takes two hours. Unloading at the mill takes one hour. If possible, the train should make two trips every day between Gannaganj and Milleria so that sugarcane from other nearby farms can also be taken to the mill from Gannaganj.
4. In the evening, Shakkarkand's employees have to come back from Milleria and Gannaganj to Shakkarpara.

The small meter-gauge train has an average speed of 20 km/h. Gannaganj and Milleria are 20 km and 30 km west of Shakkarpara, respectively. Try to make a train schedule with a minimum number of trips.

## Project 2: Picnic Pickup

Your group of five friends decides to go to Patalpaani (a nearby waterfall) for a picnic. The jeep driver has to be told when to pick you all up from your houses. You decide to make a schedule so that you can give the exact time to everyone. In residential areas, the jeep can only travel at an average speed of 20 km/h, but once it is on the main road, it can travel at 60 km/h. You want to spend five hours at the waterfall and your mother wants you back home by 6 p.m.

The distances are as follows:

Your house to Akash's house: 2 km

Akash's house to Priya's house: 1 km

Priya's house to Bholu's house: 1.5 km

Bholu's house to Ganga's place: 3 km

Ganga's place to the main road: 2 km

Distance from Ganga's place to the waterfall: 50 km

At each house, the jeep stops for five minutes for people to board, and during the return journey, it again stops for five minutes for them to get off. You can calculate the times needed for the jeep to go from one point to another. You can then find out the total time required for the trip, and accordingly tell the driver when to pick you up from your house. Fill in the schedule given below:

Driver reporting at your place: .....am

Jeep reaches Akash's house: .....am

Jeep reaches Priya's house: .....am

Jeep reaches Bholu's house: .....am

Jeep reaches Ganga's house: .....am

Jeep reaches waterfall: .....am

Jeep starts from waterfall: .....pm

Jeep reaches Ganga's house: .....pm

Jeep reaches Bholu's house: .....pm

Jeep reaches Priya's house: .....pm

Jeep reaches Akash's house: .....pm

Jeep reaches your house: .....pm

So, where do you think these relationships between distance, time, speed and acceleration are used? Two interesting examples are described in the boxes that follow.

## What Do Bats and Submarines Have in Common?

Bats are flying mammals, half the time hanging upside down from trees. Submarines are sophisticated underwater vehicles which can stay submerged for months. So what possibly can be common between them? They both calculate the motion of sound pulses to find out how far objects are from them. Bats have very poor eyesight, but you must have seen how they are able to zoom around even in the dark. This is because they use sound rather than light to 'see' things. Bats emit high-pitched sound pulses, and when these pulses hit any object like a wall, branch of a tree or an insect, they are reflected back to the bats. The bat brain can sense the time elapsed between the emitted pulse and the reflected (echo) pulse, and thereby estimate the distance of the object from itself.

Human brains and sense organs do not possess these abilities, but we have developed instruments like radar and sonar which do the same thing. Submarines use underwater sonar to 'see' what is around them in the water. Sound pulses are continuously emitted and the time for them to return after being reflected is measured (Fig. 47). Knowing the speed of sound in water, the distance of the object is estimated. Not only that, by continuously monitoring the time taken for the reflected sound to return to the source, we can find out if the object is stationary, coming towards the submarine or going away from it. Sonars are used in ships to locate submarines and fishes in deep seas, and to even study the seabed. Try to find out more examples in real life where calculations of speed, distance, time and acceleration are used.

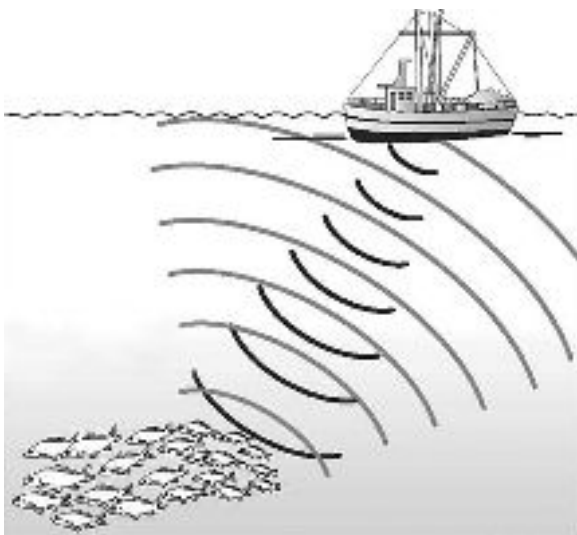


Fig. 47 Sound waves transmitted from the ship and reflected back from a shoal of fish

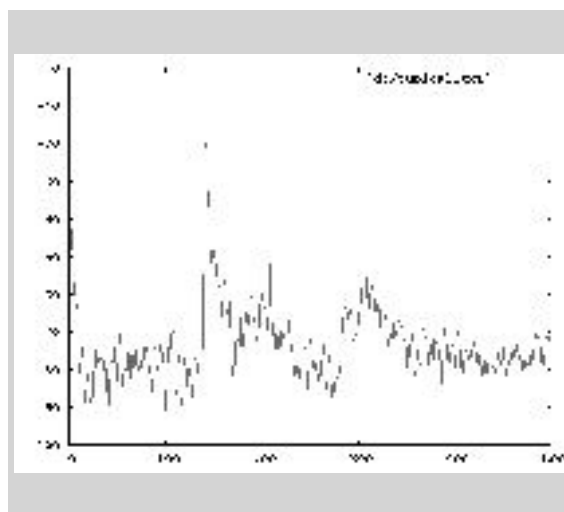


Fig. 48 Graph of active sonar data

## How Far from Us is the Moon?

Have you ever wondered how the distance between the earth and its moon came to be known? Well, many techniques have been used throughout history, but the most accurate and direct measurement has been done by using the time taken for something to go to the moon and come back. Since the moon is very far from the earth, we would prefer the motion of this thing to be very fast so that the time taken to reach the moon and come back is not too great (scientists do try to be efficient and quick!). The fastest thing known to us is light. The astronauts who landed on the moon in 1969 placed huge mirrors called retroreflectors there (Fig. 46). Then light pulses from lasers on the earth were aimed at these mirrors. The time taken for the reflected light to return was determined (Fig. 45). Because the speed of light is known with a high degree of precision, the distance from the earth to the moon can be calculated using this simple equation:

$$\text{Distance} = (\text{Speed of light} \times \text{Time taken for light pulse to come back after reflection}) \div 2$$

The time for a light pulse to go from the earth to the moon and back was around 2.5 s. Of course, the light pulse itself is of a much shorter duration than this (can you work out why this has to be so?). The average distance between Earth and its moon has thus been measured to be about 3,84,467 kilometers (238,897 miles). The earth-moon distance has been averaged because it varies a little over time—you might have read about the ‘supermoon’ occurring periodically when the moon is very close to the earth.

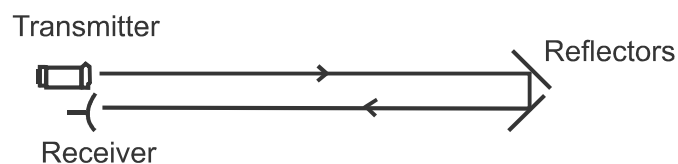


Fig. 45 Schematic diagram of a laser rangefinder



Fig. 46 Retroreflector placed on the moon by Apollo11 astronauts

By this point the students would have hopefully become interested enough in motion to be willing to extend themselves and go deeper into the subject. In the next module, we start by discussing what causes motion and what causes acceleration. We will also discuss the vector nature of velocity, acceleration and force, although the students might not yet have encountered vectors. In addition, the next module includes the historical development of the concepts of force and motion. This will help students in getting a conceptually correct understanding of the subject as well as serve as an example of how scientific theories develop.



# Science and the Scientific Method

This appendix is addressed to teachers. The evolution of the concepts of motion and force will be discussed in part 2 of this series where readers will get a flavour of the scientific approach. Two project ideas are given at the end of this appendix for teachers to use.

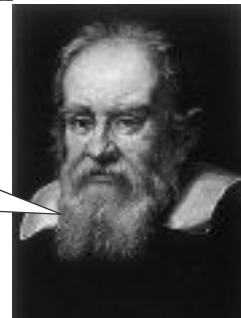
Have you ever wondered what science is and why is it considered different from other fields of study? One way of defining science is that it is a process of studying something scientifically or, in other words, that uses the scientific method. Thus, we have mathematical science, physical science, biological science and even social science. The common factor amongst all these 'sciences' is the scientific method.

The evolution of our understanding of motion and force is a very good example to see how science and the scientific method evolved over time. In the early civilizations, people used only their unaided senses to make observations and the philosopher-scientists of that time proposed a theory of motion based on such observations. One influential philosopher was Aristotle (384-322 BC). He claimed that the speed of a falling object increases in proportion to its mass (heavier objects fall faster than lighter ones). The logic of this claim was questioned by other philosophers, but a general belief in Aristotle's theory continued. Meanwhile, with progress in the techniques to measure time and distance, it was possible to carry out experimental tests of the theory of motion. Finally, in the 17<sup>th</sup> century, Galileo (1564-1642) showed by an



Heavier the falling mass,  
more is the speed

Heavy or light,  
same is the speed



More the speed,  
heavier is the mass

!!

?

experimental test and logical extrapolation that all objects dropped from the same height will reach the ground at the same time if there is no friction due to air. Several scientists continued to add their refinements to these findings with Newton (1643-1727) expressing the then available knowledge in the form of equations and laws. Newton proposed that the acceleration (rate of change in speed) of an object is proportional to the force applied on it. The mass of the object is an inherent property of the object and is constant. This became the basis for Newtonian mechanics which was considered correct and was expected to explain all the observed motions on Earth as well as all astronomical motions. However, over the course of time, some observations were found that did not fall in line with the predictions of Newton's laws. In particular, the observation that the speed of light is a constant (and does not depend on the frame of reference) called for a more comprehensive theory. Einstein, Lorentz and Poincare's works led to a more accurate theory, namely that of special relativity.

The theory that is currently accepted was proposed by Einstein (1879-1955). According to this theory, at very high speeds (near the speed of light, which is a constant), the mass of an object increases. This effect is noticeable only at very high speeds which we do not normally encounter. If you look at the dates in the preceding paragraph, you will see that from Aristotle to Galileo was a journey of 2000 years, Galileo to Newton about 85 years, and from Newton to Einstein more than 200 years! Over this time period, our understanding of motion was continuously evolving. The initial understanding was that heavier objects fall faster and that this is their intrinsic nature. This was later modified, and the understanding was then that the action of a constant gravitational field, with no other forces interfering in it, will lead to all objects falling with the same acceleration. Galileo took these laws to apply on Earth and Newton's laws of gravity extended our understanding to the motion of heavenly bodies as well. But a further refinement was added by Einstein to limit these rules to bodies moving with speeds much lower than that of light.

This is not the end. If scientists find inconsistencies in this theory, then it will be reworked. However, until now no experimental measurements have contradicted its predictions. Scientists are continuously working on devising more accurate tests of the theory. It is possible that in the near future some experiment will reveal an error in the theory and then theorists will have to get down to working out a better theory which will also explain these new results. In any field of science, you will find a similar process of continuous evolution, of an understanding of any topic that is arrived at by the cumulative work of several people over a period of time. This may be termed the scientific method.

The scientific method currently rests on three foundation stones: (a) **accurate and objective observation**, (b) **mathematical and logical analysis** and (c) **modeling**. Depending on the problem to be solved, these three tools can be used in different ways and in different orders.

A sample recipe for the scientific method can be stated as follows:

**Step No. 1:** Ask a question—why, how, what, where, when, etc. about something. This question could be triggered by a phenomenon you observed directly or by thinking about something you might have read about or heard of.

**Step No. 2:** Find out whether anyone else has any information on the subject. You do this by asking people and by reading the available literature on the subject. This is called background research. If this exercise answers your question to 'your' satisfaction, you may look for another question. It is possible that later someone else comes up with a point that you had overlooked and the currently accepted answer is found to need some modification. This going back and forth is an integral part of science. A scientific theory (in contrast to dogma), is accepted as valid only until no new fact emerges to contradict it. The moment that happens, people start working towards a new theory.

**Step No. 3:** Construct a hypothesis to answer the question. That is, you make a guess, an intelligent one, based on current knowledge. The hypothesis could be just one, or you could construct multiple hypotheses that are several, alternative explanations for your observation.

**Step No. 4:** Devise a test or an experiment to check whether your hypothesis is true or false. Here, you have to consider several things. First, the test should be fair—it should be designed so that the results are not affected by any bias in the mind of the person performing the tests (this is actually hard to implement). Second, the test should be designed such that it does not give an ambiguous answer. This can most easily be ensured by designing the test so that its result is a number. That is, you actually measure something. This means that the hypothesis you constructed in step no. 3 should be such that a suitable test can be devised. This test is what we call an experiment.

**Step No. 5:** Analyse the results obtained in the experiment. This step has to be done very carefully and rigorously so that any effect of experimental bias or imperfection is taken care of. This step may give a clear answer. Or, it may show that the experiment needs improving, or that it is not possible to perform the tests with the available resources. In that case, one has to either redesign the experiment or construct another hypothesis. Steps 3-5 very often use the reductionist approach (discussed in the main text on page 15). Whether this approach has worked or not is finally decided in step 7.

**Step No. 6:** Communicate your results to as many people as possible. This is one of the most important steps without which no progress can be made in science. The reasons are twofold. One, it allows independent repetition of the experiment by others and testing of the hypothesis by different experiments. In other words, it allows the hypothesis to be debated by a world-wide community, thus increasing the probability of spotting any loopholes in it. The second reason is that once you have found out something, based on it, another person may be able to find something else. For this, scientists need to hone their communication skills.

**Step No 7:** Once the results of your experiment are clear and their analysis done, a model or theory about the phenomenon under consideration can be developed. This usually involves making a mathematical model of the phenomenon and can be based on the compiled results of several experiments. A theory is considered valid only if it can explain all previous observations in that field. Such theories can be useful in one or more of the following ways: (a) they are expected to explain a natural phenomenon and predict its evolution (e.g., prediction of the next earthquake), (b) they can help us find

ways to control the phenomenon according to our requirements (e.g., preventing a comet from crashing into the earth), and (c) they can help us in developing new technologies to improve the quality of our lives (e.g., new sustainable sources of energy).

As you can understand, **the above recipe can have many variations depending on the type of study being done**. It may, (and usually will) require iterations at some step. All the steps need not be (and are mostly not) conducted by the same person or team, or even at the same place. Given below are some project ideas to give your students to do during their vacations. They must prepare a report giving a step by step description of how a problem was approached and solved. And if it was not solved, what the limitations were.

### **Projects:**

1. What material is the best for making cooking utensils? (Hint: List all the factors affecting the choice of material like cooking method, cost, ease of cleaning, resistance to corrosion, evenness of heating, etc. Separate out the necessary requirements and the preferable qualities. Then search for materials which fulfill these requirements. The best choice may not be any one material. The outcome can be to specify which material is best for a given set of conditions. It can also be a blueprint for the properties which an ideal material should have. This project does not necessarily involve experiments, but the children can be encouraged to test some of the facts which they would have read about. For example, they can test whether it is possible to boil water in a paper cup, or whether water boils faster in an aluminium vessel as compared to one made of steel.)

2. My grandmother says that keeping peacock feathers (*morpankh*) in a room drives away house lizards. How would you go about testing this assertion (hypothesis)?

# Graphs

This appendix includes a more detailed discussion of the graphs used to describe motion. It is in two sections. Section A describes the fundamental principles of plotting graphs and can be used for students who have little or no familiarity with graphs. Section B discusses the graphical representation of motion in continuation with the material in the main module. Section A can be skipped if students are conversant with graphs.

## A: Introduction to Graphs

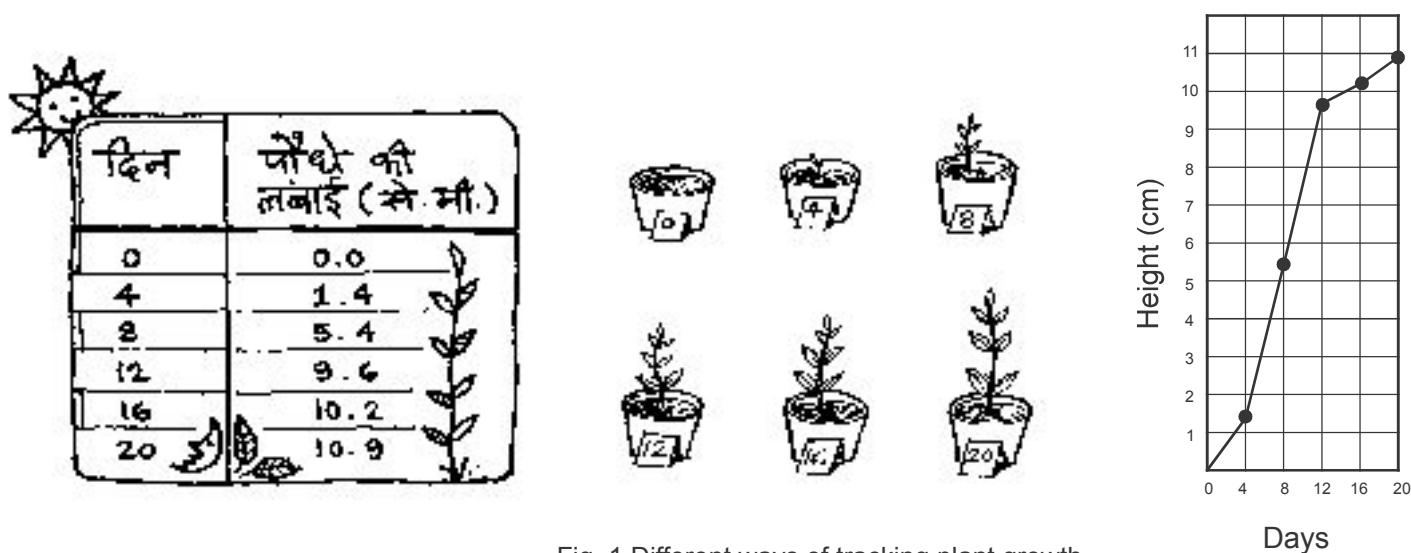


Fig. 1 Different ways of tracking plant growth

The growth of a plant (its height) is shown above in different ways: as a table, as a series of drawings and as a graph.

All three pictures tell us that over a period of 20 days the height of the plant increased continuously. However, the graph tells us so much more than the other two pictures. We can read off the measured height on every fourth day (same information as given in the table). At a glance, we can also see that the rate of increase in the plant's height has not remained constant over 20 days. The height of the plant increased at a slower rate after the 12th day. We can also estimate the plant's heights on days in-between. For example, on the 6th day the plant must have been around 3 cm in height, and on the 10th day around 7.5 cm.

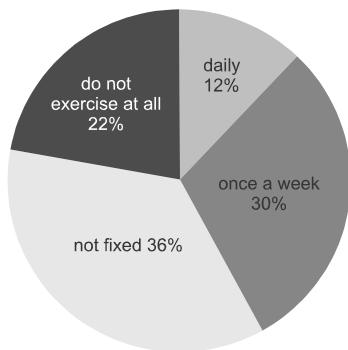
So what exactly is a graph and how do we make one? A graph is a pictorial representation of two variables, quantities that change according to some relationship between them (see the box below on types of graphs). In the example above, the number of days and the height of the plant were the two variables. The relationship between them is that the plant height increased as the days passed. In this example, 'number of days' is the independent variable, and 'plant height' the dependent variable as its value depends on how old the plant is. Making a graph is called 'plotting'.

## Types of Graphs

The graphs discussed so far are **line graphs** or line charts. They are used to depict the relationship between two quantities. This kind of graph was invented by the 17th century French philosopher-mathematician Rene Descartes (1596-1650) and provided the first systematic link between geometry and algebra. The x and y values of any point on such a graph are called its Cartesian coordinates, after Descartes. There are other kinds of graphs as well. **Bar graphs** can be used to compare more than two variables. For example, your school may use a bar graph to show the number of students passing in different classes every year. A **pie chart** is used to show the percentage distribution of values of some attribute in a given set of objects. You might have seen pie charts showing the results of opinion polls. Some examples are shown below.

Try to spot graphs in magazines, newspapers and on TV. Think about why a particular type of graph was used in that situation. Also, try to use graphs in reports you write for a project in any subject. You will find that it makes your reports better and easier to understand!

How often do you exercise?



Financial summary of a small scale company

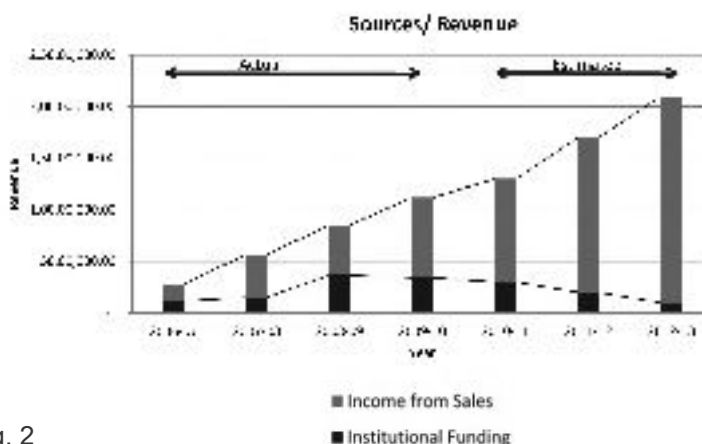


Fig. 2

## Plotting a Graph

Let us go over the basic rules for plotting a line graph. Take the example of the relationship between the side of a square and its perimeter. Table 1 shows some data to be plotted. Start by taking a graph sheet and follow the instructions given below.

Table 1

| No. | Length of the side of a square (cm) | Perimeter of the square (cm) |
|-----|-------------------------------------|------------------------------|
| 1   | 1                                   | 4                            |
| 2   | 2                                   | 8                            |
| 3   | 3                                   | 12                           |
| 4   | 4                                   | 16                           |
| 5   | 5                                   | 20                           |

## How to Draw the Axes and Plot the Data

1. Identify the two variables whose relationship is to be represented on the graph. In this case, the length of the side will be the independent variable and perimeter the dependent variable.
2. On the graph paper draw a horizontal line close to the bottom edge. Then draw a vertical line close to the left edge of paper such that it crosses the horizontal line at one point. The horizontal line is called the x-axis, and the vertical line the y-axis. Take care that both the lines are drawn on the dark lines of the graph paper (Fig. 3). The point where both these lines meet on the graph paper is called the 'Point of Origin'. The space below the x-axis and to the left of the y-axis is used for writing the description of the axes (see Fig. 3).

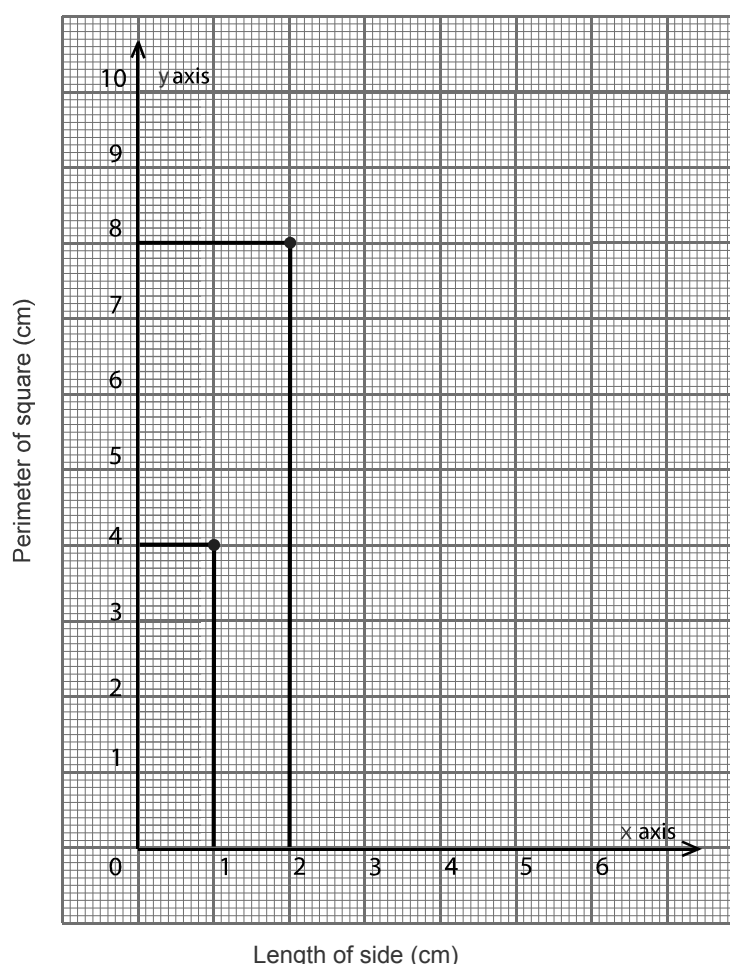


Fig. 3 Perimeter of a square vs. Length of its side

3. The independent variable (in this case, the length of the side of a square) is marked on the x-axis. The dependent variable (the square's perimeter) is marked on the y-axis.
4. Mark the point of origin as '0'. Make markings on the x-axis at 1 cm intervals and number the marks 1, 2, 3, 4, 5 and so on, from left to right. Note that in all the graphs the markings have to be equally spaced.
5. You have to plot the perimeter of the square on the y-axis. Look at the values for perimeter in table 1. The largest square has a perimeter of 20 cm. So, divide the y-axis into twenty 1 cm divisions and number them 1 to 20 from bottom to top, starting 1 cm away from the origin.

## Plotting Data Points

1. Table 1 shows that a square with a side of length 1 cm has a perimeter of 4 cm. Since the length of the side of the first square is 1 cm, draw a vertical line on the 1 cm mark of the x-axis. This line should be parallel to the y-axis (Fig. 3).
2. The perimeter of this square is 4 cm. So, draw a horizontal line at the 4 cm mark of the y-axis. This line should be parallel to the x-axis (Fig. 3).
3. Draw a circle around the point where these two lines intersect each other. This is your first data point (Fig. 3). Data points are those points on the graph paper which represent the data given in a table.
4. Plot other data points on the graph paper for the remaining four squares given in the table, in the same manner.
5. Join these points using a ruler to get a graph line. Why should you join these data points with a straight line? Think this over for a while before reading further.

Joining two data points with a straight line is known as 'linear approximation'. This means that we assume that for values of the x variable between these two points, the y variable changes linearly. How is this useful? Let us say we want to know the perimeter of a square with a side of 4.5 cm. It is not given in the table. Ordinarily, we would have to calculate the value.

However, it is straightforward to read it from the graph. Draw a vertical line at the 4.5 cm point of the x-axis. Name the point where this line meets the graph line as 'A' (Fig. 4). Draw a horizontal line parallel to the x-axis from the point A towards the y-axis. Where does this line intersect the y-axis? Read this value on the scale given on the y-axis. This is the perimeter of the square with a side of 4.5 cm. With some practice you will not need to draw the lines, you will be able to read the values by using the printed lines on the graph paper itself.



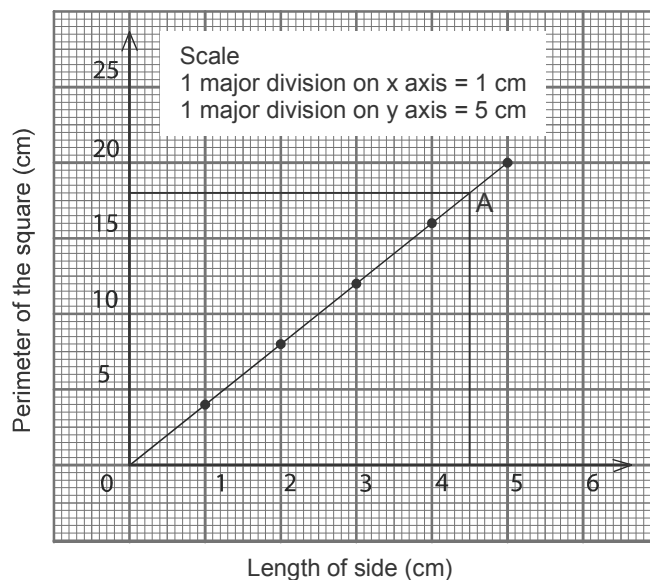


Fig. 4 Finding out the perimeter of a square with a given length from a graph

In this way, graphs are useful in giving us more information than the few values that are plotted using data given in a table. The process of estimating values between data points is called **interpolation**. Suppose we now want to know the perimeter of a square with a side of length 6 cm. Can this graph give us the answer? Extend the graph line with the help of a ruler. Now, find out the perimeter of a square that has a side of 6 cm by following the same procedure as was done for the square with side 4.5 cm. This process of extending the graph line to estimate the values beyond the known data is called **extrapolation**.

## Choosing a Scale

The ease of getting information from graphs depends a lot on the scaling. Scaling means setting an appropriate unit of the independent variable as equal to one cm on the x-axis and similarly, setting an appropriate unit of the dependent variable equal to one cm on the y-axis. While setting the scale, keep the following in mind:

1. The scale is such that you are able to show the largest value on the graph paper.
2. The scale is such that almost all of the graph area is covered.
3. Choose easily divisible units so that reading between the marked points is easy.

We will illustrate these points using two data sets. The graph paper grid we will use is 13 cm by 7 cm in size. We mark the origin at a point 2 cm from the bottom and 1 cm from the left edge of the graph paper so the length of the x-axis is 6 cm and the length of the y-axis is 11 cm.

**Example 1:** Table 2 lists the areas of squares with sides of different lengths. The maximum value for the length of the side of a square (the independent variable) is 5 cm. So, for the x-axis we can take 1 major division on the graph to be equal to 1 cm of the length of the side of a square. The maximum value for area of a square is 25 sq. cm. How do we best fit all the values for area on the y-axis? If we take 1 major division on the graph as equal to 1 sq. cm area or 2 sq. cm area, some of the points will not fall within the graph sheet. So we can take 1 major division on the axis to be equal to 5 sq. cm area. This will give us a graph as shown in Fig. 5. You can see that some of the points fall in-between the thicker graph gridlines. Try some other scales and see which one is the most convenient to plot for this data set.

Table 2

| No. | Length of one side of a square (cm) | Area of the square (sq. cm) |
|-----|-------------------------------------|-----------------------------|
| 1   | 1                                   | 1                           |
| 2   | 2                                   | 4                           |
| 3   | 3                                   | 9                           |
| 4   | 4                                   | 16                          |
| 5   | 5                                   | 25                          |

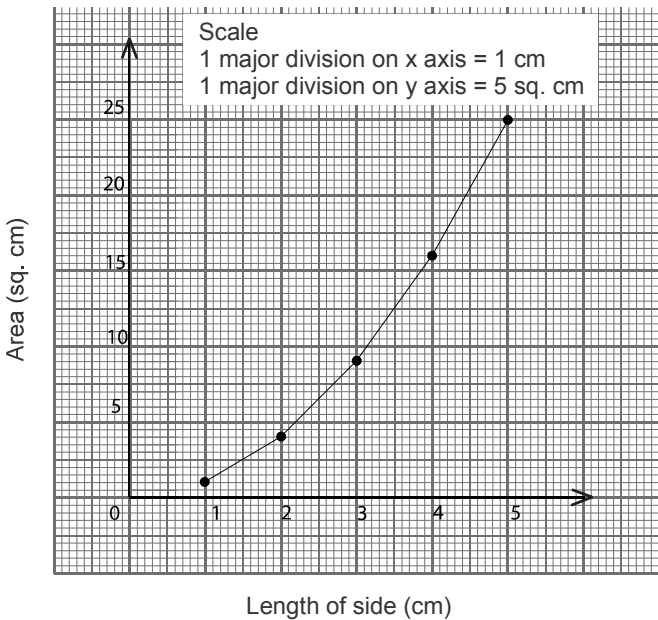


Fig. 5 Area of a square vs. Length of side

**Example 2:** The second example is that of wheat yield per acre. Here, the scales chosen are 1 major division on the x-axis = 2 acres and 1 major division on the y-axis = 2 tons. So you see, any kind of measurable quantity can be plotted on a graph.

Table 3

| Wheat yield per acre |                          |                       |
|----------------------|--------------------------|-----------------------|
| No.                  | Size of field (in acres) | Wheat yield (in tons) |
| 1                    | 1                        | 1.5                   |
| 2                    | 2                        | 3                     |
| 3                    | 3                        | 4.5                   |
| 4                    | 4                        | 6                     |
| 5                    | 5                        | 7.5                   |
| 6                    | 6                        | 9                     |
| 7                    | 7                        | 10.5                  |
| 8                    | 8                        | 12                    |
| 9                    | 9                        | 13.5                  |
| 10                   | 10                       | 15                    |

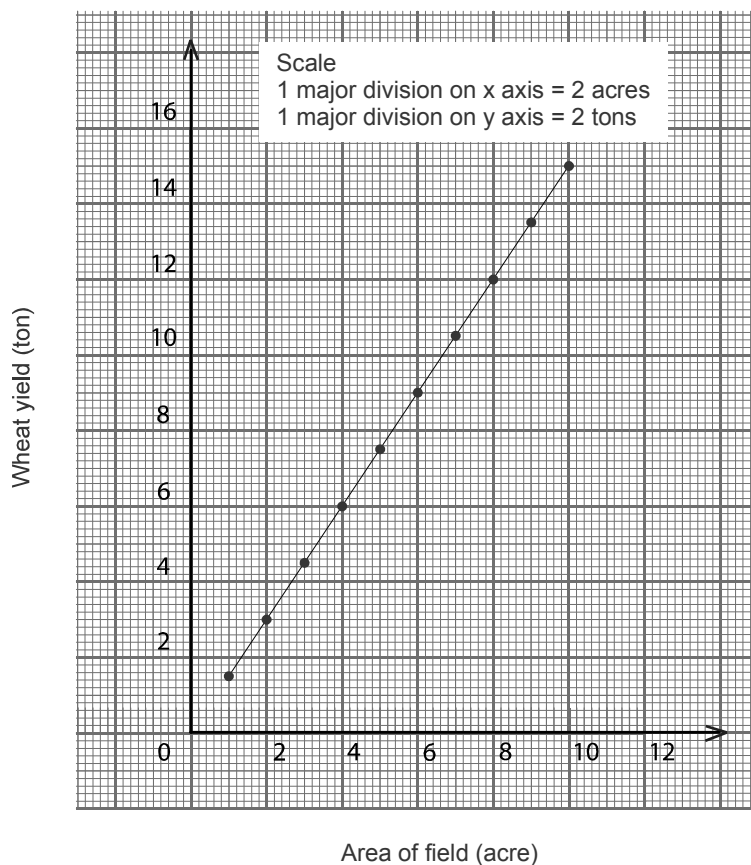


Fig. 6 Wheat yield for a given field area

## Limitations of Graphs

Like any other mathematical tool, graphs also have limitations and must be used knowing what these are:

1. The only actual information in a graph is the plotted data points.
2. There is a limit to the precision with which the points can be plotted on and read from the graph. The least count of the measuring instrument you have used will decide the minimum spacing between two consecutive data points. Since you don't have the instruments to take data for the points in-between these two, you have to make a guess for these points. For the problems considered here, it is usually safe to assume that the graph between any two data points is a straight line joining them.
3. In case of extrapolated values, one should take care to check whether the estimated value is physically possible.

In the context of motion, in one glance a graph provides a visual representation of motion. Research has revealed that students' common misconceptions in interpreting graphs of motion arise from the fact that such graphs are confused with maps of the physical routes taken by the persons or objects in motion. They often visualise the end point of a graph line as the end of the trip, or the dead end of a road. The inclined line is thought to be the slope of the road, and the points of change in the slope are perceived as the points where a traveller turns. This issue is already addressed in the example of Ritu's walk discussed in the main text. You can also use the following example to test whether the children have understood the difference between a graph and a map, and whether they can read data correctly from a graph. These basics are essential before going on to more detailed discussions on the use of graphs in understanding motion. We suggest that some time be spent to discuss in detail the ideas that students have and to correct any misconceptions before proceeding further.

Let us take the example of Munni walking from her home to school. On the next page, the drawing on the right (not to scale) is a map of the route Munni takes. On the left is a distance-time graph of her journey marked with measurements made every two minutes. The actual measurements are shown by dots. Consecutive dots are joined by straight lines. From the two pictures, answer the following:

1. Can you estimate how long Munni takes to reach her school by looking at the map?
2. By looking at the graph, can you guess how many turns there are along the road from Munni's home to her school, or the point where the road crosses the river?
3. How much distance did Munni cover from the 8th minute to the 10th minute of her journey?
4. Did Munni cover equal distances in each two-minute interval of her journey?

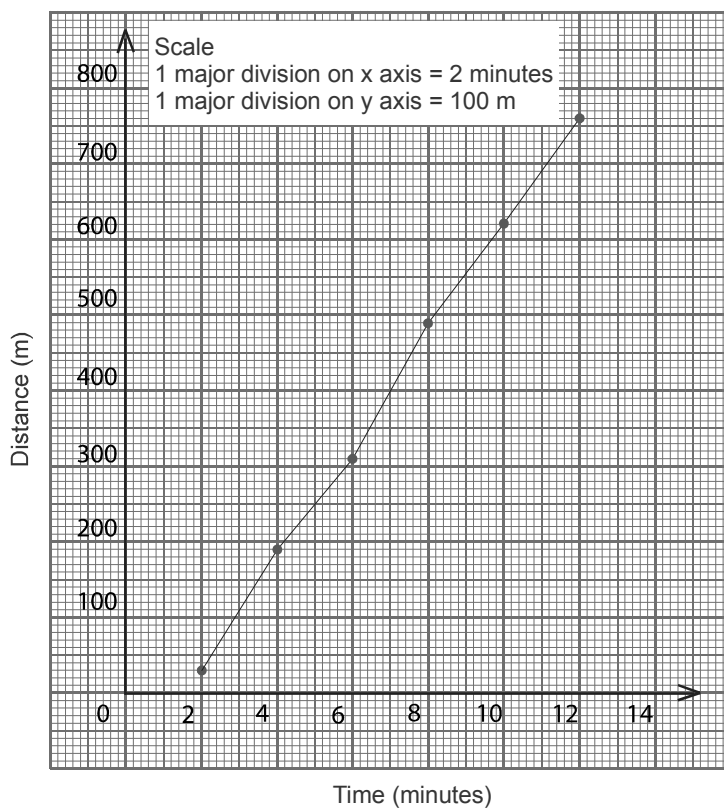


Fig. 7 Distance covered by Munni vs. Time taken

Questions 3 and 4 on the previous page are designed to test whether the students can extract information from graphs. If they find it difficult to answer these questions, the exercises given previously should be done again.

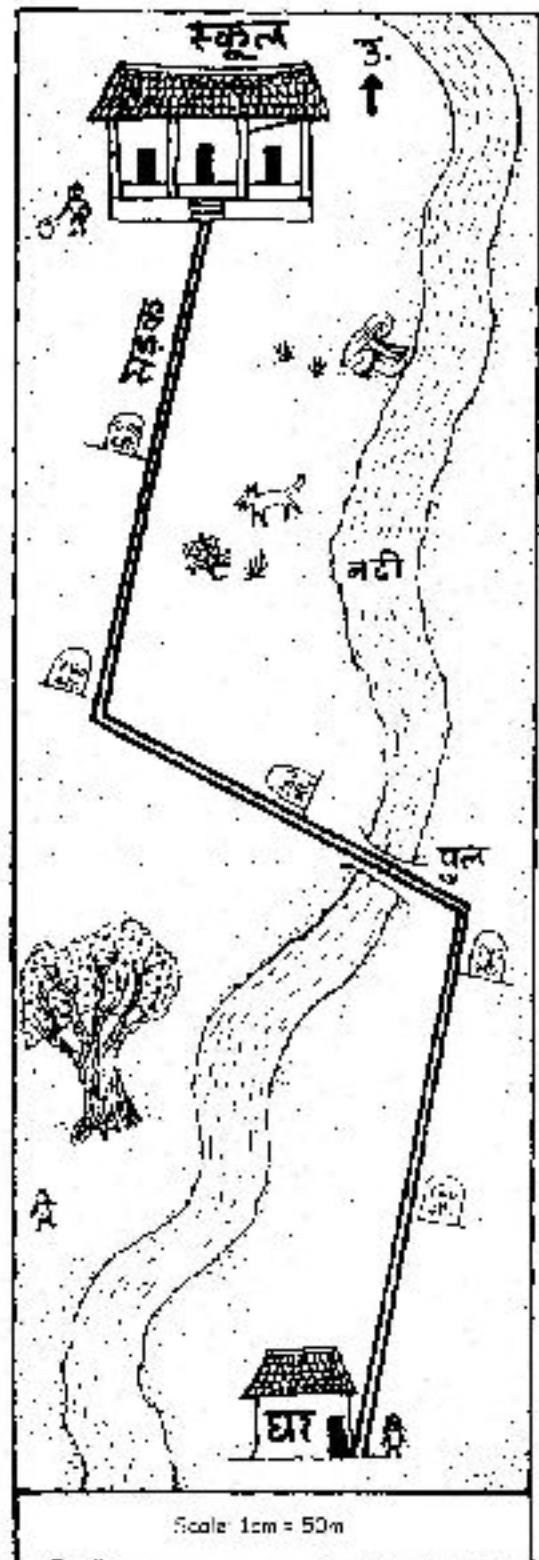


Fig. 8 Map of the route taken by Munni from her house to school

## B: Graphs of Motion

This section is a continuation of the discussion on graphs in the main text.

We have seen that the slope of a distance-time graph can give us the speed of the object in motion. We also plotted speed-time graphs. Can we get any information from the slope of a speed-time graph as well? We shall again look at the data in the table on Page 47 which gave the positions and speeds at various points in time of a body in free fall.

Table 4

| Data Point | Time (s) | Distance from the starting point (m) | Instantaneous speed (m/s) |
|------------|----------|--------------------------------------|---------------------------|
| 1          | 1        | 5                                    | 10                        |
| 2          | 2        | 20                                   | 20                        |
| 3          | 3        | 45                                   | 30                        |
| 4          | 4        | 80                                   | 40                        |
| 5          | 5        | 125                                  | 50                        |

The two graphs we drew there were like this:

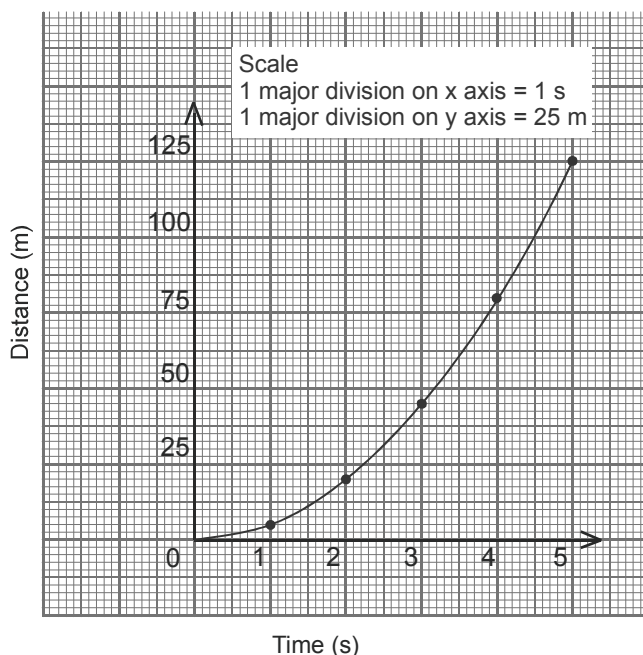


Fig. 9 Distance-time graph for a given motion

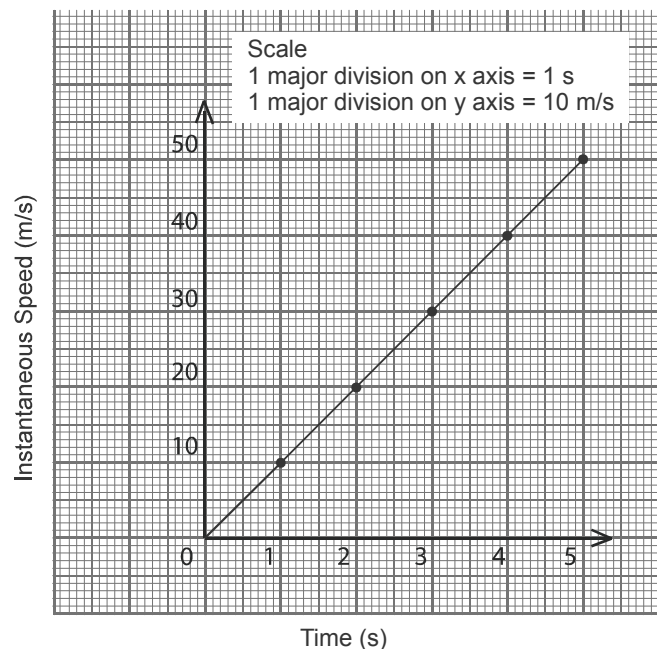


Fig. 10 Instantaneous speed vs. Time for the same motion

The slope of the speed-time graph corresponds to the ratio of the change in speed to the corresponding change in time. This, by definition, is the acceleration. Therefore, the slope of the speed-time graph gives the acceleration!

Find out the slope of the speed-time graph and check to see if it is the same as the acceleration calculated from data in the table.

The next example is designed to illustrate a few points that have not yet been covered. For one thing, the data is explicitly stated to be artificial and is used as an abstract illustration of a theory. This theory, nonetheless, is still applicable to real life situations. This method is one way of extracting underlying principles. Then the distance-time and speed-time graphs are given together to help establish the correlation between them. Also, the speed-time graph is an example of a graph that does not start from the origin, that is, the value of  $y$  is not zero at  $x = 0$ .

Following the same line of argument, we can deduce that if the speed-time graph is a straight line, the acceleration must be uniform. There is one difference however. Unlike speed, acceleration can take on negative values. The table below shows the data for distance and speed of a motion with negative acceleration and figures that follow show the corresponding distance-time and speed-time graphs.

Table 5

| Time (s) | Distance (m) | Instantaneous Speed (m/s) |
|----------|--------------|---------------------------|
| 0        | 0            | 10                        |
| 10       | 95           | 9                         |
| 20       | 180          | 8                         |
| 30       | 255          | 7                         |
| 40       | 320          | 6                         |
| 50       | 375          | 5                         |
| 60       | 420          | 4                         |
| 70       | 455          | 3                         |
| 80       | 480          | 2                         |
| 90       | 495          | 1                         |
| 100      | 500          | 0                         |

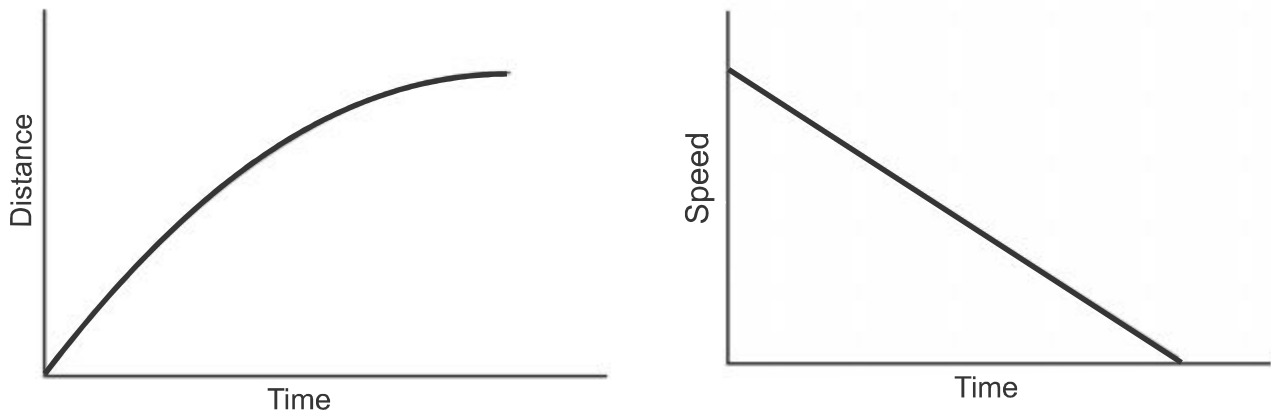


Fig.11 Graphs for motion with negative acceleration

You may note that no units are given because this is imaginary data for illustrating the concept. You can try plotting the data to see if your graphs look similar to the ones here. Let us see what the graphs tell us:

1. The distance at time  $t = 0$ , is 0. This means that we are taking the position at time  $t = 0$  to be the reference point.
2. The speed is not zero at the beginning although the distance is zero (see point 1).
3. The speed decreases with time till it reaches zero, the distance increases with time as long as the speed is not zero.

If the speed remains zero after this time, the graphs would look like the following:

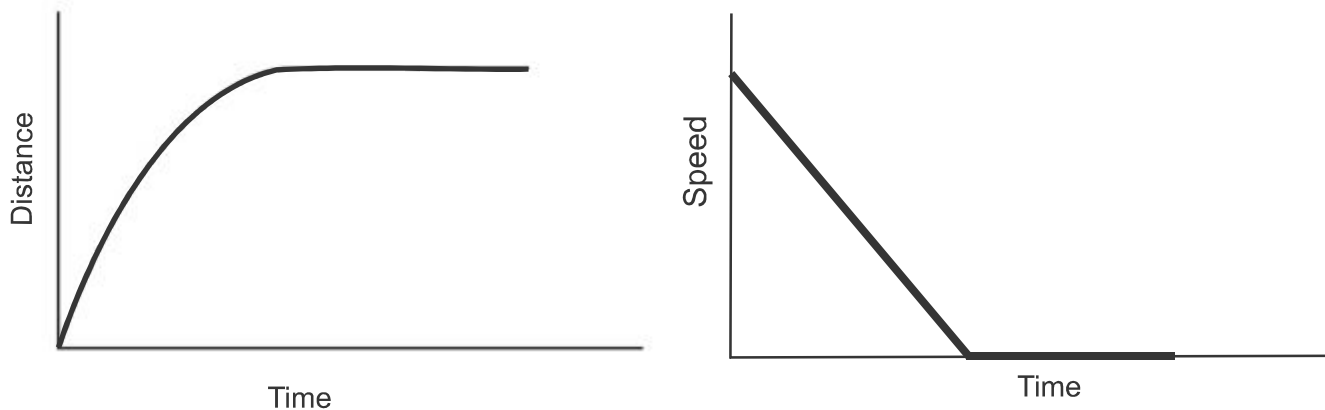


Fig.12

As you can see, once the speed becomes zero, the distance covered does not increase.



Given below are some more examples of distance-time and corresponding speed-time graphs. What can you say about the motions being depicted?

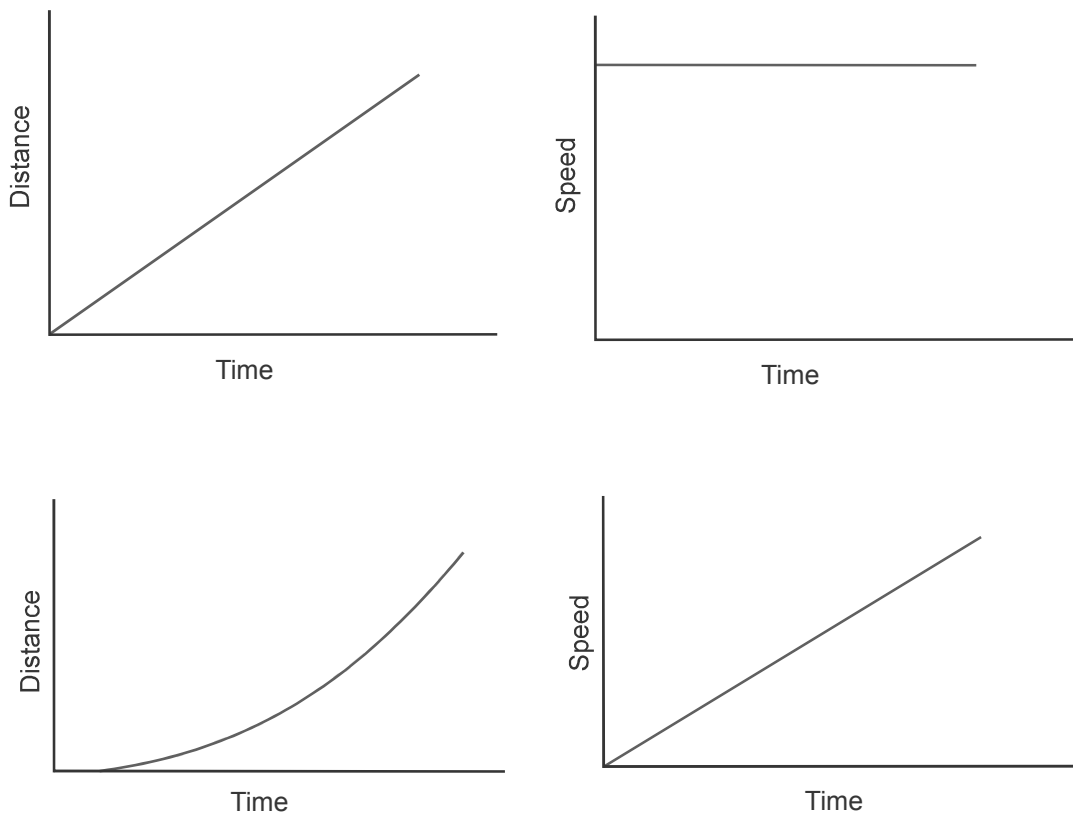


Fig.13 Distance-time graphs along with the corresponding speed-time graphs

## News Item

If you are wondering whether distance-time graphs exist only in textbooks, take a look below at a news item from 2009.

ALLAHABAD: In its continuous tryst to amalgamate modern technologies, the Allahabad division of North Central Railway is switching over to computerised charting of the movement of trains. This will ensure better and safer movement of trains running in the Allahabad division which extends from Mughalsarai to Ghaziabad near New Delhi. The computerised charting of trains is a mission critical 24x7 real time system designed to manage traffic control operations and maintain the punctuality of trains through better decision-making. Control charts, basically the time-distance graphs of the trains' motion, used by section controllers are presently manually made and interpreted. In a step towards full automation of train operations, the process of chart making and its analysis are being fully computerised. The application deals with charting the running of trains and forecasting paths for new trains automatically and efficiently. While making the computerised charting, the mail/ express trains are shown with red lines, goods trains are shown with green lines while the passenger trains are depicted with blue lines. No sooner than a train passes a particular station, the section controller gets the information through the concerned station master. He records the movement of the train on a graph known as the master chart. The distance (in kms) is shown on the x-axis while the time is depicted on the y-axis. The x-axis has the details of the various stations in a particular section. The section controller regularly updates the graph as the train surges along the railway track and records the arrival time at the different stations in his section.

When you are next stuck at a railway station waiting for a train, request the station master to show you the train control chart.

If you have access to a computer, learn how to plot graphs on it.

# Measurement: Limitations and Errors

This appendix is addressed to teachers. Therefore, the treatment is at a slightly higher level than that elsewhere. However, understanding this topic is essential to be able to guide students while they perform activities given in the main text, and to also address any questions that they may come up with while taking measurements.

We have taken measurements at several places in this module. We have also talked about the various precautions to be taken while measuring any quantity. But despite this, have you noticed that we do not get exactly the same value when we repeat a reading, even when we do our best to keep all the conditions of the experiments the same? This is a very common practical problem, and students can not appreciate it until they have taken some measurements by themselves. This is why we insist that you give every child in your class the opportunity to take measurements. Measurement is an important skill, but many times it remains implicit and we overlook many conceptual issues related to measurement. In this section we will try to deal with some of these conceptual questions.

To start with, one such issue is whether you can measure any length you like using a ruler, or any duration of time with a stopwatch. Then there is that baffling observation we discussed in the above paragraph—why are all the readings of a quantity taken under similar circumstances not exactly the same? After all, the length, or the time measured have some definite values! Do they not? So, which of the different readings is to be taken as the correct one, which one is the most accurate and are there readings which should not be used at all? These are some critical questions related to measurement. We will start by discussing questions related to the limitations of measurements, and then we will move on to discuss possible sources of inaccuracies in an experiment.

## Limitations of Measurements:

Measuring with an instrument is constrained by two major kinds of limitations: the limitations of the instrument itself, and the limitations while handling the instrument. Let us now try to understand this in detail.

Every measuring instrument has a lower limit of values it can read; it cannot measure any value that is smaller than this lower limit. An ordinary 15 cm ruler cannot measure lengths of less than 1 mm. Your wristwatch can only measure times equal to or more than one second. The minimum value which an instrument can measure with accuracy is called the 'Least Count' of the instrument. If the smallest markings on your ruler are at a distance of 1 cm, its least count is 1 cm. If the distance between any line or marking on your ruler and the one immediately following it is 1 mm, its least count is 1 mm, and if you have to measure a length less than 1 mm, you can't use this ruler. This is a limitation of the instrument

that we had mentioned earlier. Ask children in your class to draw a line of 3.41 cm so they understand the problems in drawing a line of exactly that length.

Now, it may be that the actual accuracy of a measurement is less than the best possible with that measuring device. A good example is time measurement using a stopwatch, as described earlier on. The stopwatch we used has a least count of 1 centi-second (a 100th part of a second). But the least time anyone needs to just switch it on and off is between 15 to 20 centi-seconds. Therefore, you cannot measure a time less than or close to these values with accuracy.

## Accuracy in an Experiment:

Even if we measure a time period that falls within the limits of a measuring instrument and its handling, we might not get accurate results. This can happen because of several other errors that are possible during an experiment. These errors possible in any measurement are generally classified into two major categories: **systematic errors** and **random errors**.

### Systematic Errors:

Systematic errors are those errors which occur due to a faulty experimental setup or faulty measuring instruments.

#### a) Systematic errors due to a faulty experimental setup:

Suppose in the inclined plane activity, the plank is placed such that the ball does not roll straight down and instead rolls towards one side. In that case, we will be measuring the time for a different distance while assuming that it is the time taken for the ball to cross the segments we have marked, and our results will reflect this error. Thus, we need to identify possible systematic errors beforehand and rectify them in advance. Like in this case, you would have to adjust the plank such that the ball rolls straight down.

#### b) Systematic errors due to a faulty instrument:

If a measuring instrument is not calibrated correctly then the readings you take with it will be incorrect. This problem may become evident when a measured value differs from the actual value by a fixed proportion of the latter. For example, if all the inch divisions on a ruler are marked incorrectly and each one is 5% shorter than the actual length of 1 inch, then a measured value of 4 inches will differ from the actual length by 5% of 4 inches. Similarly, a measured value of 6 inches will differ from the actual length by 5% of 6 inches.

Such an error may occur not only because of incorrect calibration. It is also possible that the instrument being used is deformed—if a wooden meter ruler is bent slightly then it will consistently measure incorrectly.

Another kind of systematic error that can occur is a zero-setting error—arising because of incorrect measurement with respect to the reference point, or the ‘zero’ of the instrument. For example, if you

measure the length of a thread with one end held at the '1 cm' mark of the ruler and the other at the '10 cm' mark, then its length is not 10 cm. The length of the thread in this case is the difference between the two points:  $10\text{ cm} - 1\text{ cm} = 9\text{ cm}$ . This is a mistake students often make. In this case, each measurement of a given length will be incorrect by a constant value—1 cm. This also means that if you take one measurement with the '0 cm' mark as the reference point, and others with some other reference points, like in the example above, then the distance will have to be calculated according to the reference point in each instance.

Systematic errors are not always easy to spot, but they can be removed if we look for possible sources of such errors in advance. Then the necessary changes can be made in the experimental setup, or the equipment being used. To have confidence in the readings taken during any experiment, one has to ensure calibration of all the instruments being used.

### Random Errors:

Random errors are those errors which occur by chance. Every time data is noted, it is impossible to exactly replicate the conditions they are noted in. This reflects in the data in the form of variations in readings.

Consider the same inclined plane experiment. It is difficult to mark the exact instant of time when the ball crosses from one segment to the next one because of the minimum reaction times of the handlers noting the crossing of the ball and pressing the buttons on the stopwatch. Only by increasing the number of readings and taking the average of those readings can this error be minimized. A basic understanding of statistics tells us that the average of these readings gets closer to the actual value as the number of readings increases. So, if you take 8-10 readings, you are likely to get an average value very close to the actual value. None of these readings are more accurate than the others. Only the average value of all the readings will give the most accurate value.

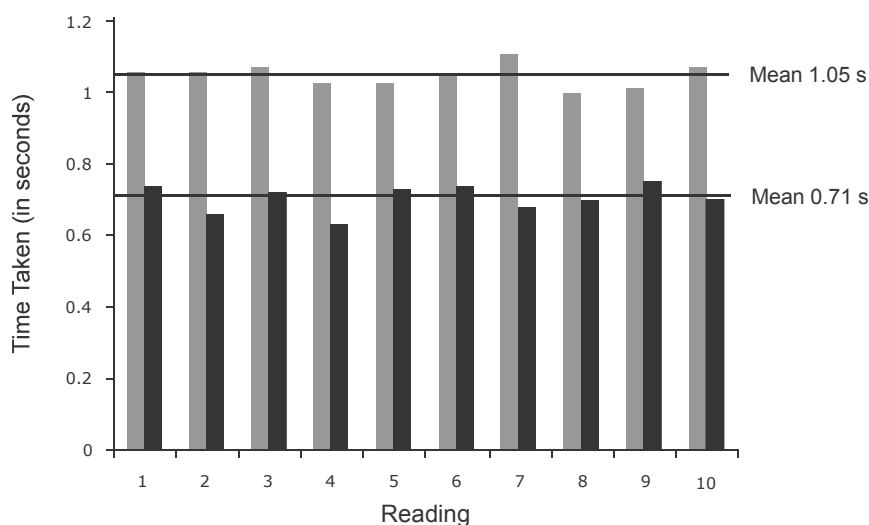
The following table contains the sample data taken for the inclined plane experiment. The data shows the time taken by the ball to cross the two segments of 45 cm each (R1, R2, etc. represent the different readings):

Table 1

|                  | R1   | R2   | R3   | R4   | R5   | R6   | R7   | R8   | R9   | R10  |
|------------------|------|------|------|------|------|------|------|------|------|------|
| <b>Segment 1</b> | 1.06 | 1.06 | 1.07 | 1.03 | 1.03 | 1.05 | 1.11 | 1.00 | 1.01 | 1.07 |
| <b>Segment 2</b> | 0.74 | 0.66 | 0.72 | 0.63 | 0.73 | 0.74 | 0.68 | 0.70 | 0.75 | 0.70 |

Assuming that the observers have carefully recorded this data knowing how to use the instruments correctly and their limitations, you can see that the values are not the same in all the readings for either segment. If we plot this data, we see that the deviation from the mean is in both directions—there are values greater as well as lesser than the mean.

The grey bars in the graph show the time taken to cross segment 1 and the black bars show the time taken by the ball to cross segment 2. The mean time for the ball to cross segment 1 turns out to be 1.05 seconds and that to cross segment 2 comes to 0.71 seconds. If you draw two horizontal lines representing the two means for both segments, you can see that the deviation of the data from the average value is on both sides, above and below the lines.



However, even with our best efforts, this deviation of the data, the difference in the time cannot be avoided completely and we can minimize it only by repeating the experiment 8-10 times. So, even if we repeat the experiment several times, we cannot get rid of this error completely. Some error will always be there. Now, if you want to know how close your experimental value is to the theoretical value, that is, if you want to quantify this error while doing a verification experiment, you can calculate the 'percentage error' in your experiment—a commonly used method to describe the experimental error. It is nothing but a ratio of the difference between the actual and the expected or standard value, to the expected value.

The numerical form of percentage error is:

$$\% \text{ error} = \frac{(\text{Actual Measurement} - \text{Expected Value}) \times 100}{\text{Expected Value}}$$

If you don't know the theoretical or expected value in advance, you cannot know the magnitude of this error. But you could design an experiment to calculate 'the acceleration due to gravity', for which the theoretical value is  $9.8 \text{ m/s}^2$ . This is called a verification experiment. In that case, if your experimental value comes out to be  $9.6 \text{ m/s}^2$ , your percent error will be –

$$\begin{aligned}\% \text{ error} &= (9.6 - 9.8) \times 100 \div 9.8 \\ &= 2 \% \text{ approximately}\end{aligned}$$

If you get a high percentage error (say more than 10%), you should revise your entire experiment starting from its design to the recording of observations.

When doing an experiment for which the expected answer is not known, we need to check the range of readings we get. If the range is about 10 % of the average reading, we need to revise the experiment while looking out for sources of error.

$$\% \text{ error} = \frac{(\text{Maximum Value} - \text{Average Value}) \times 100}{\text{Average Value}}$$

Thus, we see that in spite of working within the limits of the measuring instrument and with all the necessary precautions, we cannot get rid of all errors. The point, that there is always a variation in the readings, should be reinforced when you discuss issues related to measurement in your class. You may like to do some more measurement activities and then discuss conceptual matters by referring to the data you have collected. One of these activities could be to measure the length of a table. You can discuss the basic precautions that need to be taken while measuring length, and then ask the students to measure the length of the table as accurately as possible. Once everybody is done with taking the measurements, discuss the variation in the data as well as other issues related to errors and accuracy in measurement.

# Suggestions for Projects

The following projects are meant to give students the opportunity to design their own experiments for solving a given problem.

## Measuring Average Speed:

You can ask students to design experiments for estimating the average speeds for some of the following objects in motion. It is possible that they will find that some of the speeds cannot actually be measured with locally available equipment. However, it will still be a good exercise to find out which speeds cannot be measured locally and why this should be so. (Assume all these motions are along straight lines.) Also discuss what the errors in the proposed methods could be and how they can be minimised.

1. A cricket ball thrown from the outfield to the wicket-keeper
2. The wind
3. A cloud
4. A raindrop
5. A hand moving back and forth as fast as possible between two fixed points
6. The tip of a swinging cricket bat
7. A person while walking on level ground, climbing up stairs and going down stairs
8. A camera shutter opening and closing
9. The tip of the growing nail
10. A bird flying
11. Water flowing down a drain
12. The centre of a vibrating guitar string



## Measuring Acceleration:

1. In the inclined plane experiment that you did, think of the ways you can calculate the acceleration of the rolling ball.
2. Assuming that the brakes of a cycle provide uniform deceleration, can you design ways to measure that deceleration.

## Measuring the Average Speed for Running a Distance of 20 Meters:

To measure the time for running this distance, the activity should be performed in an open ground to provide sufficient space for running. Ask one of the students in the group to run up a 20 meters long straight path. The student noting the time taken for the other to run this distance should be standing at the finishing line. He/she will tell the runner when to start running and will start the stopwatch at the same time and will stop the timer exactly when the runner crosses the finish line. Note down the readings in the following table:

Table 1

| S.No. | Name | Total Distance (m) | Time Taken (s) | Average Speed (m/s) |
|-------|------|--------------------|----------------|---------------------|
| 1     |      | 20                 |                |                     |
| 2     |      | 20                 |                |                     |
| 3     |      | 20                 |                |                     |
| 4     |      | 20                 |                |                     |
| 5     |      | 20                 |                |                     |

This activity, in contrast to the other activities in the module, is to be done in an open ground. It can be used as a refreshing change if the students show signs of tiring of classroom work. Once the data has been taken, a discussion on possible errors and how to improve the accuracy of the experiment can be conducted.

## Finding the Speed of a Rolling Marble:

To measure the time of a rolling marble, ask the students to form teams of 3-4 members. Let one student in each team roll the marble a definite distance away, say 2 meters. To note the time taken, use the same procedure as mentioned in the last activity. An inclined plane can be used instead of a flat ground for rolling the marble. Ask the students to calculate the speed of the rolling marble on their own and to also tabulate the data for the other team members.

## Measuring the Time for Blinking an Eyelid

An interesting activity of measuring the time for blinking an eyelid can be performed in which the students can be asked to blink their eyelids 20 times continuously at a normal rate. During the repeated blinking by one of the students, ask another to note the time taken for this blinking using a stopwatch. Perform this activity involving all the group members, i.e., all the students in the group can blink their eyelids one by one to compare the fastness or slowness of blinking.

This activity is somewhat different from the previous activities and doesn't give the sense of speed. In this activity, instead of measuring distance, the number of times the eyelid blinks during a given time is being counted. The number of blinks per unit time is known as the frequency of blinking. The concept of frequency can also give the sense of fastness or slowness of an object executing periodic motion.

## Measuring the Time for Chopping Clay

This may be another interesting activity brings in the idea of frequency once again. Roll some clay (plasticine) into a cylinder of roughly 20 cm length and 1 cm diameter and ask one of the students to chop the roll with a knife, say 20 cuts. This can be repeated by all the students of the group, i.e., one by one all the students can chop the roll. To get the respective frequencies of chopping, ask the students to count the number of pieces of the roll and divide it by the observed time to estimate their frequency of chopping. As they finish this exercise, they could be asked to take an average of their time readings for each case.

# Problem Set

## Conceptual Questions

1. Discuss why trains coming from the opposite direction appear to be moving very fast and why a train that is overtaking your train seems to be moving very slowly.
2. It was raining heavily one day while Amit was cycling to school and so he had his umbrella open. When he cycled past some people waiting for a bus, Amit was surprised to see that they were all holding their umbrellas upright while he himself was holding his umbrella tilted well forward. He wondered why this should be so. Can you think of an answer for his question?
3. If your younger sister asks you to estimate the average speed of a bird flying overhead, what would be your answer? How would you check whether your estimate is correct?
4. If you are asked to measure the instantaneous speed of any object, for example, the instantaneous speed of a bullet as it leaves the barrel of a rifle, explain how you would do this. What are the factors you would need to know in order to measure this speed? Can you think of more than one way of doing this?
5. An owl sat on a tall tree holding a stone in its beak. After some time the stone slipped from its beak and fell down. Here are a few statements describing the motion of that stone. Tick the correct statement(s).
  - a. The stone starts falling with zero speed. (   )
  - b. The stone will fall in a straight line. (   )
  - c. The stone falls with a constant speed till it reaches the ground. (   )
  - d. Its speed keeps on increasing continuously from the beginning till it reaches the ground. (   )
  - e. The speed acquires its maximum value just before striking the ground. (   )
6. If a brick falls accidentally from the 4<sup>th</sup> floor of a construction site, what will be its acceleration when it starts to fall? What will be its acceleration just before it reaches the ground? Will the time taken by the brick to cross the windows of each floor be the same (assume that the windows are identical)? Will any of your answers be different if the brick were to fall from the 10<sup>th</sup> floor?

7. Three different types of inclined planes are shown in Fig.1. In which case will the acceleration be uniform and in which will it change? If the acceleration is changing, do you expect it to increase or decrease?

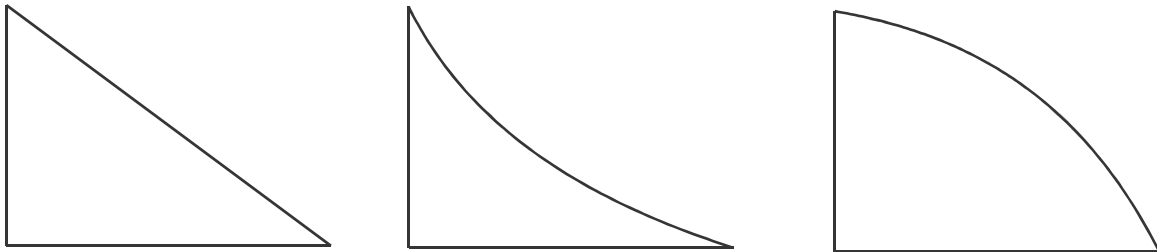


Fig. 1 Inclined planes with different slopes

8. The following position-time graph (Fig. 2) depicts the motion of a cart. Answer the following questions on the basis of the information given in the graph:

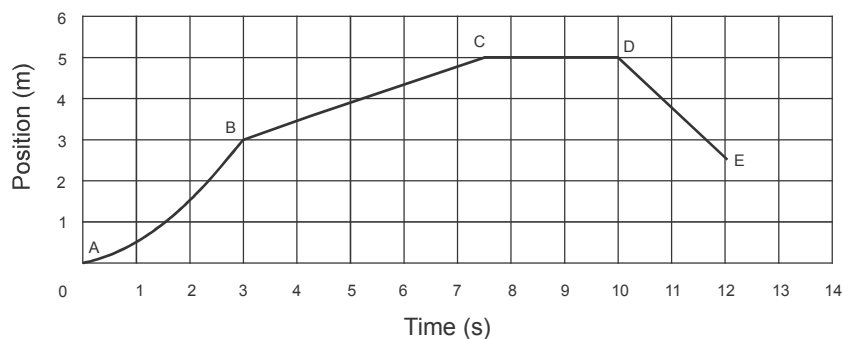


Fig. 2 Position-time graph of a cart in motion

- a. During which interval was the cart at rest?
  - i. AB
  - ii. BC
  - iii. CD
  - iv. DE
- b. During which interval was the cart moving towards the original position?
  - i. AB
  - ii. BC
  - iii. CD
  - iv. DE
- c. During which of these two intervals, BC and DE, was the cart traveling faster?
  - i. DE
  - ii. BC

9. A helicopter is flying east with a uniform speed of 50 km/h. Which graph(s) correctly represent the motion of the helicopter (Fig. 3)?

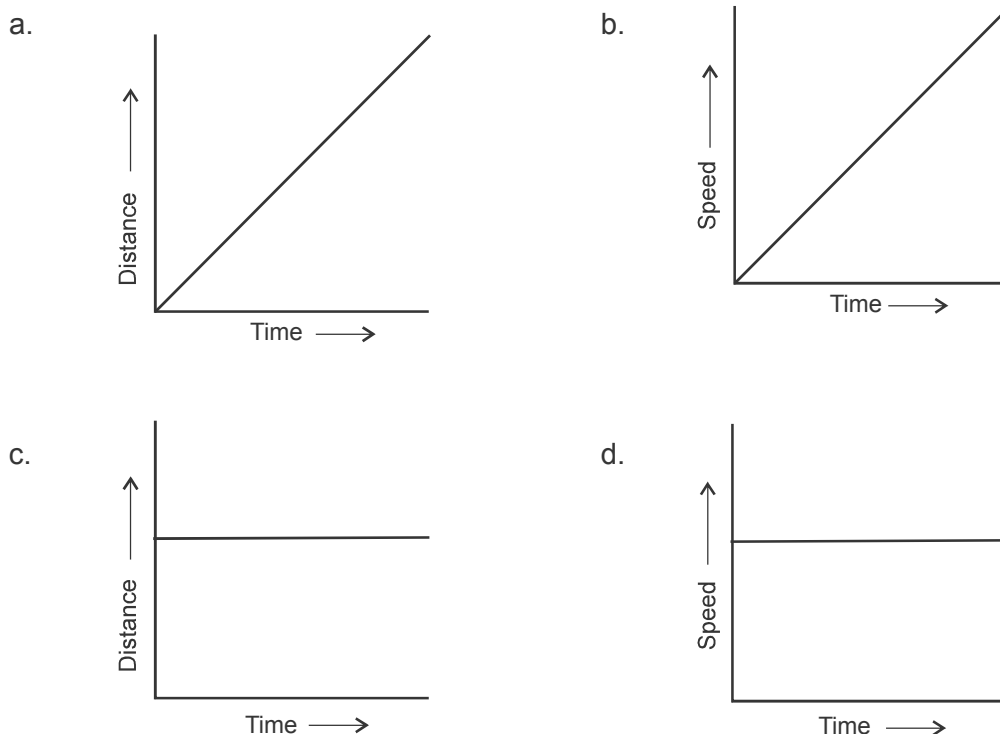


Fig. 3 Distance-time and speed-time graphs for the helicopter

10. This is a very old story. You may have heard it many times before. It is the story of the race between a rabbit and a tortoise. The two have a bet on who will win the race. The rabbit takes off swiftly while the tortoise begins with a slow and steady pace. The rabbit initially runs far ahead of the tortoise. But then, he decides to rest under a tree for a while and falls asleep. The tortoise, meanwhile, continues to forge ahead steadily. When the rabbit wakes up, he runs to the finishing post. But, alas! when he reaches the finish line he finds that the tortoise has already won the race.

Illustrate the race between the rabbit and the tortoise in the form of a graph.

11. The winner of the 2012 Olympic gold medal in the men's 400 m hurdle race took 47.63 s while the gold medallist in the women's 400 m hurdle race took 52.70 s.

Runners are supposed to clear ten hurdles in the 400 m hurdle race. Assuming that the hurdles are evenly spaced around the track, draw the speed-time graph of an athlete participating in the 400 m hurdle race. Will the graph be different for a 400 m race with no hurdles? What about a 400 m relay race?

12. Fig. 4 shows the distance-time graph for Ramesh's (black circles) and Hamid's (white squares) journeys. Write a story about this journey on the basis of the graph.

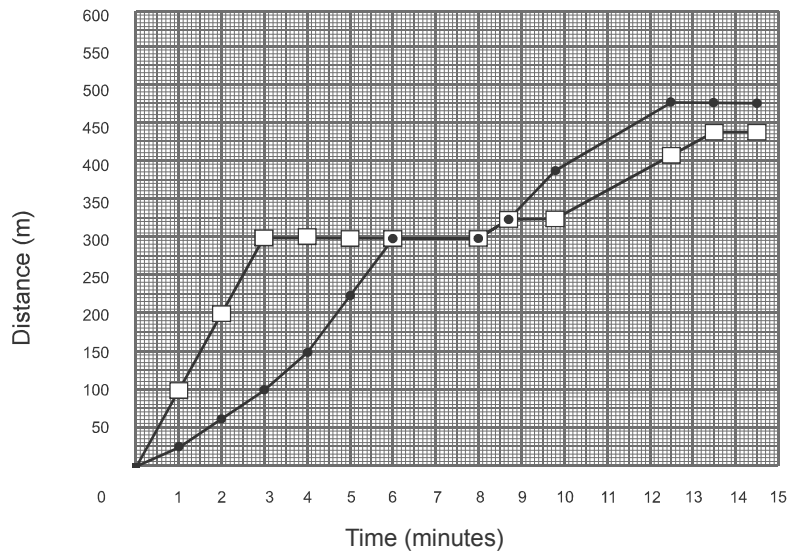


Fig. 4 Distance-time graph depicting Ramesh's and Hamid's motion

13. If you ride a bicycle, you may have noticed that you don't have any problem pedalling with uniform motion when the road is straight and level. But when you climb uphill, your speed decreases. On the other hand, when you go downhill your speed increases and the bicycle moves really fast. Fig. 5 shows the graph of a bicycle trip taken by Kamala. Look at the graph and say which of the following statements are true:

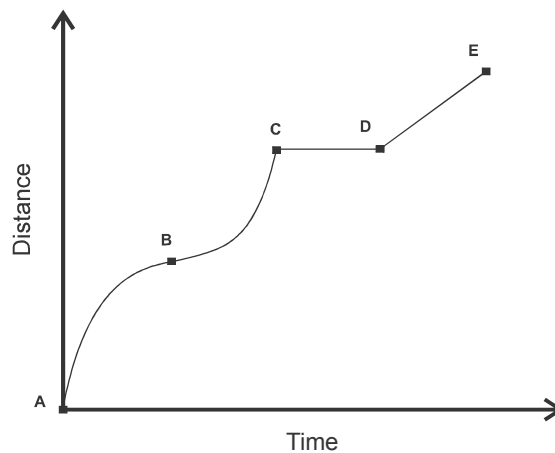


Fig. 5 Graph showing the details of Kamala's cycle ride

- a. Kamala cycled up a slope, then went down a slope, then stopped and rested for some time. She then cycled on a level road. ( )
  - b. Kamala cycled uphill continuously. ( )
  - c. Kamala first went downhill, then on a level road, then climbed uphill and finally rested. ( )
  - d. Kamala first cycled uphill, then stopped and rested for some time because she was tired, then cycled on a level road and finally rode downhill. ( )
  - e. None of these. ( )
14. Can a motorbike moving initially at 80 km/h and a car moving initially at 40 km/h be made to accelerate by an equal amount?
15. The speed of a moving object is zero at some point of time in its path. Which of the following statement(s) is/are correct?
- a. The acceleration at that point will be zero. ( )
  - b. If the acceleration remains zero for next 10 seconds after that point, the speed will also be zero in that interval. ( )
  - c. If the speed is zero for next 10 seconds after that point, the acceleration will also be zero in that interval. ( )
16. A ball is thrown vertically upwards from the edge of a cliff and it is noticed that it lands on the ground below the cliff. If it were to be thrown downwards from the same place with the same speed, would its speed just before landing be greater, lesser or the same as before?

## Numerical Problems

17. A 500 m long train is moving with a uniform speed of 10 m/s. Calculate the time taken by the train to cross (i) a 250 m long bridge, (ii) an electric pole.
18. Two cars travel along the same road in the same direction from the same starting point. However, one car starts at 10 AM and maintains a speed of 40 km/h, while the other car starts 1 hour later and maintains a speed of 60 km/h. How many hours will it take for the second car to overtake the first car? How far would it have traveled by then?

19. Shreya walked at a speed of 6 km/h for 1 km and 8 km/h for the next 1 km. If she had to cover the same distance in the same amount of time but maintain a uniform speed throughout the journey, at what speed would she have to walk? Is it the same as the average of the two speeds?
20. What is your average speed in each of these cases?
- You run 100 m at a speed of 5 m/s and then you walk 100 m at a speed of 1 m/s.
  - You run for 100 s at a speed of 5 m/s and then you walk for 100 s at a speed of 1 m/s.
21. The following table shows four positions of an object as it traveled at a constant speed.

Table 1

| Position (cm) | Time (s) |
|---------------|----------|
| 0             | 0        |
| 3             | 9        |
| 5             | 15       |
| 7             | 21       |

- How fast was it traveling in the 20<sup>th</sup> second?
  - What was the position of the object after 18 seconds?
22. A bus increases its speed from 60 km/h to 70 km/h in 5 seconds while a cyclist goes from rest to 10 km/h in the same period of time. Which of the two undergoes greater acceleration?
23. Kamal and Sona decided to visit Ramu's sweet shop after school. When they were about to leave school, the teacher called Sona. So, Kamal left for the sweet shop alone. After a short while, Sona came running and caught up with Kamal. They then went together to Ramu's shop and ate *jalebis* there. The entire episode is shown in the form of a graph using different symbols for showing how Kamal and Sona travelled (Fig. 6).



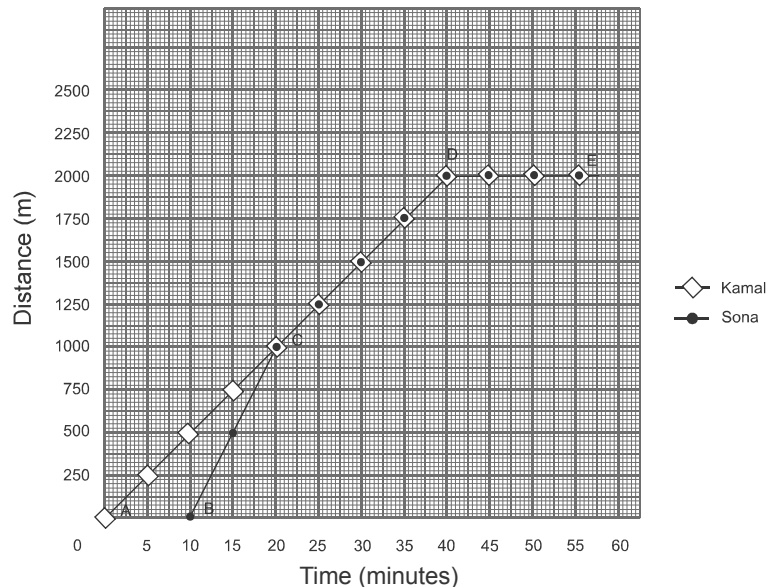


Fig. 6 Distance-time graph for Kamal and Sona's trip to Ramu's sweet shop

Look at the graph and answer the following questions:

- What was Kamal's average speed till he reached the sweetshop?
- How long was Sona detained by her teacher?
- How much time did Sona take to catch up with Kamal?
- What was Sona's average speed while she was running?
- How far from the school did Sona finally catch up with Kamal?
- What is the distance between the school and Ramu's shop?
- How far did they walk together?
- For how much time did they walk together?

24. You may have read the story of the flying turtle. Two swans held the ends of a stick firmly in their beaks and the turtle hung on to the stick with its teeth. The swans flew carrying the turtle along. As they were flying 180 metres above a lake, the beautiful scene below overwhelmed the turtle. He couldn't contain his excitement and exclaimed "Wow!" The remaining story of the turtle's flight is given in table 2.

- Draw a graph depicting the turtle's motion.
- What does the graph look like?

Table 2

| Time (s) | Distance fallen by the turtle (m) |
|----------|-----------------------------------|
| 0        | 0                                 |
| 1        | 5                                 |
| 2        | 20                                |
| 3        | 45                                |
| 4        | 80                                |
| 5        | 125                               |
| 6        | 180                               |

- c. Can you say, on the basis of this graph, whether the motion of the turtle was uniform or non-uniform?
  - d. How long did it take for the turtle to fall into the lake from the height of 180 metres?
  - e. What was the average speed of the turtle during its fall?
  - f. Can you say what the turtle's speed at  $t = 2$  s was?
25. A careful analysis of the motion of a moving object yielded some information which is plotted in the graph below (Fig. 7). Now answer the following questions:

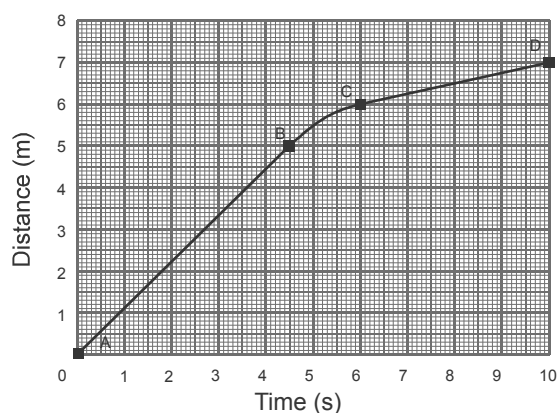


Fig. 7 Distance-time graph showing an object in motion

- a. When was the speed the greatest? What was the value of the speed at that time?
- b. At what moment or in which time interval was the speed least? What was the speed at that time?
- c. What was the speed at  $t = 1$  s?

- d. What was the speed at  $t = 8 \text{ s}$ ?
  - e. How far did the object move from time  $t = 7 \text{ s}$  to  $t = 9.5 \text{ s}$ ?
  - f. What was the average speed between  $t = 4 \text{ s}$  and  $t = 7 \text{ s}$ ?
26. A loaded truck left the warehouse with the meter reading 12345 km. When it got back after three days the reading was 13245 km. What was the average speed of the truck during this period?
27. A cyclist starting from rest accelerates at the rate of  $1 \text{ m/s}^2$  for 4 seconds. What will be her speed after 4 seconds? What distance would she have covered by then?
28. A bullet is fired from a rifle which has a 1 m long barrel. The bullet leaves the barrel with a uniform speed of 500 m/s and enters a concrete wall. The bullet penetrates 5 cm into the wall before it comes to rest.
- a. How much time would the bullet have spent in the barrel assuming the acceleration in the barrel is constant?
  - b. Find the deceleration in the bullet's speed once it hits the concrete wall.
29. An object starts moving with an initial speed of 3 m/s and it experiences a uniform acceleration of  $1 \text{ m/s}^2$  in the same direction.
- a. Find the distance travelled by it in the first two seconds.
  - b. How much time would it take to reach a speed of 7 m/s?
  - c. How much distance would it have covered before reaching a speed of 7 m/s?
30. Note: This problem involves some algebraic calculations and it is suggested that this problem should not be given to the students unless they have a good command over algebra.

Two objects A and B start from rest and move for an equal amount of time in a straight line. Object A has acceleration 'a' for the first half of the total time and '2a' for the second half. Object B has an acceleration of '2a' for the first half and 'a' for the second half. Which object will cover a greater distance? Calculate the distances travelled by both the objects and their final speeds.

31. A superfast train was traveling at 72 km/h when the driver noticed a buffalo caught in the tracks and braked immediately in order to save its life. If the brakes cause a deceleration of  $1 \text{ m/s}^2$  and the buffalo was at a distance of 250 m from the train when the driver saw it, would the buffalo survive?

32. Clouds are generally found at a height of 1500 m above the ground. Falling from this height, what would be the speed of raindrops when they reach the ground?

Actually, raindrops face a lot of air resistance in-between and are slowed down quite a bit. Otherwise it would not have been safe to walk outside during a rainstorm.

33. Due to a small leakage in a pipe, drops of water fall at equal time intervals on the floor 9 meters below. The first drop strikes the floor at the same instant the fourth drop begins to fall. How far would the second and third drops have fallen when the first one strikes the floor?

34. A ball is thrown upwards with a speed of 20 m/s from the edge of a 60 m high cliff. After some time, it starts falling down. It passes through the starting point and continues to fall further to the base of the cliff.

a. What is the maximum height attained by the ball?

b. How much time will it take to pass its starting point on the way down?

c. How much time will it take to reach the base of the cliff?

Assume that the acceleration due to gravity is roughly equal to  $10 \text{ m/s}^2$ .

# Answer Sheet

## Conceptual Questions

1. Hint: Think in terms of the 'point of reference'.
2. The point of reference is different for Amit as compared to the people standing still. So, the perceived motion of the raindrops by these two groups will be different with respect to both the magnitude as well as the direction of the raindrops.
3. Hint: To measure the average speed of an object, you will have to mark a distance and note down the time taken in covering that distance.
4. Hint: If the bullet is fired horizontally, its speed in that direction will not change even after it leaves the barrel. Apply equations of motion.
5. Hint: All freely falling bodies fall with a constant acceleration (acceleration due to gravity) irrespective of the height from where they start falling. In any accelerated motion, the speed increases continuously and so the time taken to cover the same distance will keep on decreasing.
6. Hint: Same as question 5.
7. Hint: The slope of an inclined plane will govern the acceleration of the rolling ball. Higher the slope, greater the value of acceleration.
8. Hint: The slope of a line in a distance-time graph depicts speed. A steeper slope means greater speed. A horizontal line in a distance-time graph means that the distance covered is not changing with time, that is, the object is at rest.
9. The speed-time graph of a uniform motion will be a horizontal line. Since the distance will increase linearly with time, the distance-time graph will be a straight line with some slope.
14. Yes. Acceleration is the rate of change of speed. It should not be confused with the speed itself.
15. b and c
16. The speed would remain the same in both the cases. In the first case, when the ball is thrown upwards, its speed keeps on decreasing till it comes to rest. Then it comes back and by the time it passes through the same point, it attains the same speed. The rest of the story will be the same in both the cases.

## Numerical Problems

17. Train length = 500 m,

Speed of the train = 10 m/s

First case:

The distance traveled by the train to cross the bridge = 500 m + 250 m = 750 m

Suppose the time taken by the train to cross the bridge is 't' seconds.

As average speed = Distance traveled ÷ Time taken

$$10 \text{ m/s} = 750 \text{ m/t}$$

$$t = 75 \text{ s}$$

Ans

Second case:

The distance traveled by the train to cross an electric pole will be the same as the length of the train because the width of a typical electric pole is negligible in comparison to the length of the train. The pole can therefore be treated as a point.

Here again, if the time taken to cross the pole is assumed to be 't' seconds:

Using, average speed = Distance traveled ÷ Time taken

$$10 \text{ m/s} = 500 \text{ m/t}$$

$$t = 50 \text{ s}$$

Ans

18. The speed of the first car = 40 km/h

The speed of the second car = 60 km/h

Suppose the second car overtakes the first car after 't' hours. By this time, the first car would have traveled for (t+1) hours and the distances traveled by the two cars will be the same.

Using, average speed = distance traveled/time taken, and equating the distances traveled by the two cars, we can say:

$$40 \text{ km/h} \times (t+1) = 60 \text{ km/h} \times t$$

$$t = 2 \text{ h}$$

This means that after two hours of travel, the second car will overtake the first car.

Ans

The distance traveled by the cars will be 60 km/h × t = 120 km.

Ans

19. Total distance traveled by Shreya = 1 km + 1 km = 2 km

Suppose the time taken by her to cover the first half is  $t_1$  hours.

Applying the equation: average speed = distance travelled  $\div$  time taken,

$$6 \text{ km/h} = (1 \div t_1) \text{ km/h}$$

$$t_1 = \frac{1}{6} \text{ h}$$

Similarly, if the time taken to cover the second half is  $t_2$  hours

Applying the equation: average speed = distance traveled  $\div$  time taken,

$$8 \text{ km/h} = (1 \div t_2) \text{ km/h}$$

$$t_2 = \frac{1}{8} \text{ h}$$

$$\text{Total time taken by her} = t_1 + t_2 = \left(\frac{1}{6} + \frac{1}{8}\right) \text{ h} = \frac{7}{24} \text{ h}$$

If she has to travel the same 2 km walk in  $\frac{7}{24}$  h but with a uniform speed, her speed will be:

$$\text{Speed} = 2 \text{ km} \div \left(\frac{7}{24}\right) \text{ h}$$

$$= \frac{48}{7} \text{ km/h Ans}$$

$$< 7 \text{ km/h (arithmetic mean of the two speeds)}$$

Ans

20. a. Average Speed = Distance traveled  $\div$  Time taken

$$\text{Total distance traveled} = 100 \text{ m} + 100 \text{ m} = 200 \text{ m}$$

$$\text{Time taken to cross the first segment} = \text{Distance traveled} \div \text{Average speed}$$

$$= (100 \text{ m}) \div (5 \text{ m/s})$$

$$= 20 \text{ s}$$

$$\text{Time taken to cross the second segment} = \text{Distance traveled} \div \text{Average speed}$$

$$= (100 \text{ m}) \div (1 \text{ m/s})$$

$$= 100 \text{ s}$$

$$\text{Total time taken} = 20 \text{ s} + 100 \text{ s} = 120 \text{ s}$$

$$\text{Average speed} = 200 \text{ m} \div 120 \text{ s} = 1.67 \text{ m/s}$$

Ans

b. Average Speed = Distance traveled ÷ Time taken

$$\text{Total time taken} = 100 \text{ s} + 100 \text{ s} = 200 \text{ s}$$

$$\text{Distance traveled during the first 100 s} = \text{Time taken} \times \text{Average speed}$$

$$= (100 \text{ s}) \times (5 \text{ m/s})$$

$$= 500 \text{ m}$$

$$\text{Distance traveled during the second 100 s} = \text{Time taken} \times \text{Average speed}$$

$$= (100 \text{ s}) \times (1 \text{ m/s})$$

$$= 100 \text{ m}$$

$$\text{Total distance traveled} = 500 \text{ m} + 100 \text{ m} = 600 \text{ m}$$

$$\text{Average speed} = 600 \text{ m} \div 200 \text{ s} = 3 \text{ m/s}$$

Ans

21. Since the speed is constant, it will remain same for the 20<sup>th</sup> second as well.

$$\text{Speed for the first interval} = \text{Change in position} \div \text{Time taken}$$

$$= (3 - 0) \text{ cm} \div 9 \text{ s}$$

$$= \frac{1}{3} \text{ cm/s}$$

$$= 0.33 \text{ cm/s}$$

$$\text{Speed in the 20<sup>th</sup> second} = 0.33 \text{ cm/s}$$

Ans

$$\text{After 18 seconds, the distance traveled} = \text{speed} \times \text{time}$$

$$= \frac{1}{3} \text{ cm/s} \times 18 \text{ s}$$

$$= 6 \text{ cm}$$

Ans

22. Acceleration of the car = Change in speed ÷ Time taken

$$= (70 - 60) \text{ km/h} \div 5 \text{ s}$$

$$= 10 \text{ km/h} \div 5 \text{ s}$$

$$= (10 \times 1000) \div (5 \times 3600) \text{ m/s}^2$$

$$= \frac{5}{9} \text{ m/s}^2$$

Ans



Acceleration of the cycle = Change in speed  $\div$  Time taken

$$= (10 - 0) \text{ km/h} \div 5 \text{ s}$$

$$= 10 \text{ km/h} \div 5 \text{ s}$$

$$= (10 \times 1000) \div (5 \times 3600) \text{ m/s}^2$$

$$= \frac{5}{9} \text{ m/s}^2$$

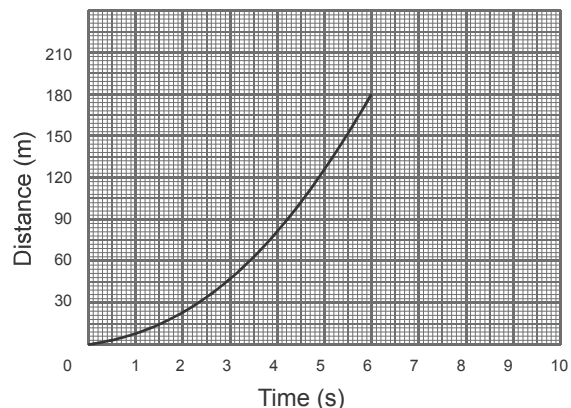
Ans

23. a. The distance traveled by Kamal in 40 minutes is 2000 meters. So, her speed is  $(2000 \div 40) \text{ m/minute} = 50 \text{ m/minute}$ .
- b. Sona started after 10 minutes (point B in the graph).
- c. Sona joined Kamal at point C, which corresponds to  $t = 20$  minutes. So, the time taken by Sona to catch up with Kamal is  $(20 - 10) \text{ minutes} = 10 \text{ minutes}$ .
- d. Sona ran between point B and C. The distance traveled by her is 1000 m in 10 minutes. So her average speed would be  $1000 \text{ m} / 10 \text{ minutes} = 100 \text{ m/minute}$ .
- e. 1000 m. (Refer to point C in the graph).
- f. 2000 m. (Refer to point D in the graph).
- g. The distance covered together is the distance between point C and point D as read on the y-axis of the graph =  $(2000 - 1000) \text{ m} = 1000 \text{ m}$ .
- h. The time they traveled together is the time interval between point C and point D as read on the x-axis of the graph =  $(40 - 20) \text{ minutes} = 20 \text{ minutes}$ .

24. a. Distance-time graph.
- b. A curved line with an increasing slope.
- c. Since the slope of the curve is not constant, the motion of the turtle cannot be uniform.
- d. 6 seconds.
- e. Total distance traveled = 180 m

$$\text{Total time taken} = 6 \text{ s}$$

$$\text{Average speed} = 180 \text{ m} \div 6 \text{ s} = 30 \text{ m/s}$$



Distance-time graph showing the turtle's position at different times after it lets go of the stick

- f. 20 m/s (Read the slope of the curve in the distance-time graph at  $t = 2$  s. Alternatively, apply equations of motion to find out the speed at  $t = 2$  s.)

25. a. In segment AB, Speed =  $5 \text{ m} \div 4.5 \text{ s} = 1.11 \text{ m/s}$

b. In segment CD, Speed =  $1 \text{ m} \div 4 \text{ s} = 0.25 \text{ m/s}$

c. 1.11 m/s

d. 0.25 m/s

e. Position at  $t = 7$  s, is 6.25 m and position at  $t = 9.5$  s, is 6.75 m.

Hence, the distance traveled =  $(6.75 - 6.25) \text{ m} = 0.5 \text{ m}$

f. Average speed = Total distance covered  $\div$  Time taken

$$= (6.25 - 4.5) \text{ m} \div (7 - 4) \text{ s}$$

$$= 1.75 \text{ m} \div 3 \text{ s}$$

$$= 0.58 \text{ m/s}$$

Ans

26. The total distance traveled by the truck =  $(13,245 - 12,345) \text{ km} = 900 \text{ km}$

The time taken to cover this distance = 3 days

Average speed = Total distance traveled  $\div$  Time taken =  $(900 \div 3) \text{ km/day} = 300 \text{ km/day}$

27. Given,  $u = 0 \text{ m/s}$ ,  $a = 1 \text{ m/s}^2$  and  $t = 4 \text{ s}$

Applying the first equation of motion,  $v = u + at$

$$= 0 \text{ m/s} + (1 \text{ m/s}^2 \times 4 \text{ s})$$

$$= 4 \text{ m/s}$$

Ans

Applying the second equation of motion,  $s = ut + \frac{1}{2}at^2$

$$= (0 \text{ m/s} \times 4 \text{ s}) + (\frac{1}{2} \times 1 \text{ m/s}^2 \times 4 \text{ s}^2)$$

$$= 8 \text{ m}$$

Ans

28. a.  $u = 0 \text{ m/s}$ ,  $v = 500 \text{ m/s}$ ,  $s = 1 \text{ m}$ , acceleration is constant (say 'a')

Suppose the time taken by the bullet in the barrel, which is to be calculated, is 't'.

Applying the first equation of motion,  $v = a t = 500 \text{ m/s}$

Applying the second equation of motion,  $s = ut + \frac{1}{2}at^2$

$$\begin{aligned} 1 &= 0 \times t + \frac{1}{2}at \times t \\ &= \frac{1}{2} \times 500 \text{ m/s} \times t \\ &= 250 \text{ m/s} \times t \end{aligned}$$

$$\therefore t = 4 \text{ milliseconds}$$

Ans

(1000 milliseconds = 1 second)

- b. Given,  $u = 500 \text{ m/s}$ ,  $v = 0 \text{ m/s}$  and  $s = 5 \text{ cm} = 0.05 \text{ m}$

Applying third equation of motion,  $v^2 = u^2 + 2as$

$$0 \text{ m/s}^2 = (500 \text{ m/s})^2 + 2 \times a \times 0.05 \text{ m}$$

$$\therefore a = -25,00,000 \text{ m/s}^2 \text{ (Too much!)}$$

Ans

Since a concrete wall will stop the bullet, it will decelerate. Therefore, the negative value of 'a' is justified.

29.  $u = 3 \text{ m/s}$ ,  $a = 1 \text{ m/s}^2$

- a. 8 m (Apply the second equation of motion) Ans

- b. 4 s (Apply the first equation of motion)

Ans

- c. 20 m (Apply the third equation of motion)

Ans

30. Second case. (Hint: For simplicity, assume the total time of travel is  $2t$  and apply the equations of motion for each half.)

31. Speed of the train =  $72 \text{ km/h} = 20 \text{ m/s}$

$$\text{Deceleration} = 1 \text{ m/s}^2$$

To save the buffalo's life, the driver should be able to stop the train before 250 m.

Suppose the train travels distance 's' before it comes to a stop.

Applying the third equation of motion,  $v^2 = u^2 + 2as$

$$0 = 20^2 + 2 \times (-1) \times s$$

$$\therefore s = 200 \text{ m}$$

The train will stop at 200 m and the buffalo will be safe.

Ans

32.  $s = 1500 \text{ m}$ ,  $u = 0$ ,  $a = 10 \text{ m/s}^2$

Applying the third equation of motion,  $v^2 = u^2 + 2as$

$$v^2 = 2 \times 10 \times 1500$$

$$v^2 = 30000$$

$$v = 173.2 \text{ m/s}$$

Ans

33. Suppose the time interval between any two consequent drops is 't'. So, the first drop would have traveled for time '3t' while the second and third drops would have traveled for times '2t' and 't' times, respectively.

Applying the second equation of motion for the motion of the first drop,

$$s = ut + \frac{1}{2}at^2$$

$$9 = 0 + \frac{1}{2}g(3t)^2$$

$$t^2 = \frac{2}{g} \dots\dots\dots(1)$$

For the second drop:

Suppose the distance covered is  $h_2$ .

Applying the second equation of motion,

$$s = ut + \frac{1}{2}at^2$$

$$h_2 = 0 + \frac{1}{2}g(2t)^2$$

$$h_2 = 2gt^2$$

Putting in the value of  $t^2$  from equation (1) above:

$$h_2 = 2g \times (2/g)$$

$$h_2 = 4 \text{ m}$$

Similarly, for the third drop:

Suppose the distance covered is  $h_3$ .

Applying second equation of motion,  $s = ut + \frac{1}{2}at^2$

$$h_3 = 0 + \frac{1}{2}g(t)^2$$

$$h_3 = \frac{1}{2}gt^2$$

Putting in the value of  $t^2$  from equation (1):

$$h_3 = \frac{1}{2}g \times (2/g)$$

$$h_3 = 1 \text{ m}$$

The second and third drops will be 4 m and 1 m below the drip point respectively when the first drop reaches the ground. Ans

34. If we assume the vertically upward direction as positive and take 'a' to be approximately  $10 \text{ m/s}^2$ , then:

$$u = 20 \text{ m/s}, v = 0, a = -10 \text{ m/s}^2$$

- a. Suppose the maximum height attained by the ball is 'h'.

Applying third equation of motion,  $v^2 = u^2 + 2as$

$$0 = (20 \text{ m/s})^2 + 2 \times (-10 \text{ m/s}^2) \times h$$

$$\therefore h = 20 \text{ m} \quad \text{Ans}$$

- b. In the case when motion is linear but back and forth along a line, the distance traveled by the object is measured as the shortest distance between the starting point and the end point. This is because of the vector nature of various related physical quantities and the relationship between them which will be discussed in detail in the second part of this series.

In this case, when the object is passing through its original position, the shortest distance between the starting point and the end point will be zero which means,  $s = 0$ .

$u = 20 \text{ m/s}$  and,  $a = -10 \text{ m/s}^2$  (acceleration and the direction of motion at the start are in the opposite direction. So gravitational acceleration will actually be decelerating the motion.)

Now, applying second equation of motion,  $s = ut + \frac{1}{2}at^2$

$$0 = 20 \text{ m/s} \times t + \frac{1}{2}(-10 \text{ m/s}^2) \times t^2$$

$$0 = 20t - 5t^2$$

$$0 = 5t(4-t)$$

$$\therefore t = 0 \text{ s or } 4 \text{ s}$$

Since  $t = 0$  corresponds to the starting time, the ball will pass through the same position after 4 seconds. Ans

c. The total time taken by the ball to reach the ground can be calculated in two parts:

1. Time taken by the ball in coming to its starting position, and
2. Time taken by the ball to go further and reach the ground.

We have already calculated the time taken by the ball to come to its original position and that is 4 s.

Suppose the ball takes 't' seconds more to reach the ground,

Applying second equation of motion,  $s = ut + \frac{1}{2}at^2$

$$\therefore 60 \text{ m} = 20 \text{ m/s} \times t + \frac{1}{2} \times (10 \text{ m/s}^2) \times t^2$$

Re-arranging quantities on either side of the equation:

$$5t^2 + 20t - 60 = 0$$

$$t^2 + 4t - 12 = 0$$

$$t^2 + 6t - 2t - 12 = 0$$

$$t(t+6) - 2(t+6) = 0$$

$$(t+6)(t-2) = 0$$

$$\therefore \text{Either } t-2 = 0 \text{ or } t+6 = 0$$

$$\therefore t = 2 \text{ s or } t = -6 \text{ s}$$

Since  $t = -6 \text{ s}$  represents a meaningless quantity,  $t = 2 \text{ s}$  will be the time taken by the ball to reach the ground after crossing the starting position.

Therefore, the ball will reach the ground in  $4+2 = 6$  seconds. Ans

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This module was conceptualised and written mainly by Rama Chari, Himanshu Srivastava and Pragya Shrivastava, with preliminary inputs from Pallavi Sukhtantar and Vikram Chourey.

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The sequence of concepts in this module was worked out on the basis of several teacher training sessions. Some sections of the module were tried out in a few schools in Indore. The feedback from these sessions has been invaluable in giving shape to the final version of this module.

The method for measuring acceleration that was used in the development of the module was possible because of a set-up designed by the Whirlybird Electronics Pvt. Ltd., Mumbai.

The illustrations and lay-out have been prepared by Shweta Raina and Jitendra Thakur, respectively. Some of the photographs are from teacher training sessions in Indore.



## Eklavya

Eklavya is a non-government registered society working in the fields of education and people's science since its inception in 1982. Its main aim is to develop educational practices and materials related to a child's environment that are based on play, activities and creative learning.

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# Motion and Force

## Part 1 - Motion

Force and Motion is considered one of the fundamental topics in science and is therefore taught in middle and high schools. However, the topic is treated in a perfunctory manner, forgetting that the current understanding of motion, and the development of concepts like speed and acceleration took place over a period of two thousand years.

We have tried to tackle these difficult concepts in the modules on Force and Motion. In this, the first module, we have concentrated on describing motion in a scientific manner. The module is primarily aimed at teachers. It presents a sequence of activities worked out on the basis of detailed discussions with subject experts and feedback from teacher-training sessions that lead to an understanding of Motion.

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